Chapter 6
Energy Production

6.1 Energy Production

Energy production mainly involves converting one form of energy into another form that is needed the most. For example, the sources of chemical energy from fossil fuels and nuclear resources are used to produce approximately 90% of the world's electricity. Petroleum (also known as crude oil) as a fossil fuel is another main source of energy. After refining the petroleum into its fraction, various fuels such as gasoline, kerosene, diesel, and fuel oil are produced. Therefore, energy production mainly involves the conversion of existing fossil fuels and nuclear resources as well as the renewable energy sources into those forms of energy needed the most in a certain application. There are various forms of energy production in the world, each with its own risks and benefits. The world's power demand is expected to rise by 60% by 2030. *Cogeneration* is the production of more than one useful form of energy (such as process heat and electric power) from the same energy source [31, 33].

6.2 Electric Power Production

A fossil fuel power plant produces electricity by converting fossil fuel energy into mechanical work. The two major power plant systems are based on the steam turbine cycle and the gas turbine cycle mostly using fossil fuels. The steam cycle relies on the Rankine cycle in which high pressure and high temperature steam produced in a boiler is expanded through a turbine that drives an electric generator. The discharged steam from the turbine gives up its heat of condensation in a condenser to a heat sink such as water from a river or a lake. The condensate is pumped back into the boiler to restart a new cycle. The heat taken up by the cooling water in the condenser is dissipated mostly through cooling towers into the atmosphere (see Fig. 6.1).

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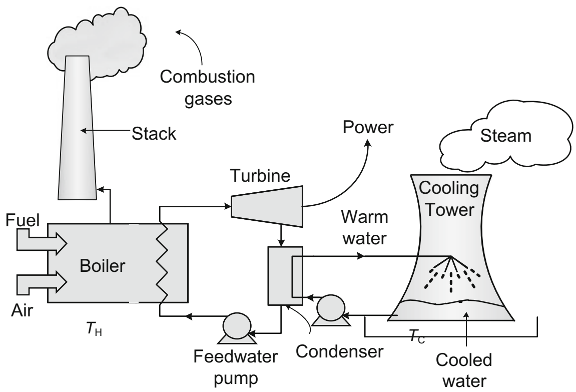


Fig. 6.1 Schematic of a steam power plant

The fundamental principles of electricity generation were discovered during the 1820s and the early 1830s by the British scientist Michael Faraday. Based on Faraday's work, electricity is produced by the movement of a loop of wire, or disc of copper between the poles of a magnet. Most of the electricity produced results from steam turbines. The combustion of fossil fuels supplies most of the heat to these turbines, with a significant fraction from nuclear fission and some from renewable resources. Today, steam turbines produce about 80% of the electric power in the world by using a variety of heat sources.

Assuming that nitrogen remains inert, the complete combustion of a fossil fuel using air as the oxygen source may be represented approximately by the following reaction:

$$C_xH_y + \left(x+\frac{y}{4}\right)O_2 + 3.76\left(x+\frac{y}{4}\right)N_2 \rightarrow xCO_2 + \left(\frac{y}{2}\right)H_2O - 3.76\left(x+\frac{y}{4}\right)N_2 + \text{Heat} \tag{6.1}$$

where C_xH_y represents a fossil fuel consisting of carbon (C) and hydrogen (H) only, with stoichiometric coefficients of x and y, respectively, depending on the fuel type. A fossil fuel, such as coal or natural gas, may have other elements such as sulfur and compounds such as minerals beside the carbon and hydrogen. A simple example is the combustion of coal (taken here as consisting of pure carbon): $C + O_2 \rightarrow CO_2$. Coal is prepared by grinding it to powder and mixing it with air which preheats the coal to drive off excess moisture content and transports it to the furnace.

Most of the electricity in the United States is produced using steam turbines. In steam turbines, coal or natural gas is burned in a furnace to heat water in a boiler to produce steam. In 2009, 45% of the Country's nearly 4 trillion kWh of electricity used coal as its source of energy. Example 6.1 illustrates the analysis of an adiabatic steam turbine. Figure 6.2 shows the various energy sources used to produce electricity in the U.S. Centralized power production became possible when it was recognized that alternating current power lines can transport electricity at very low

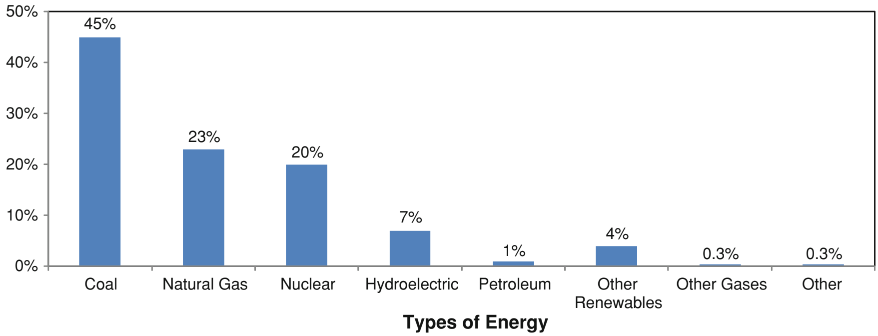


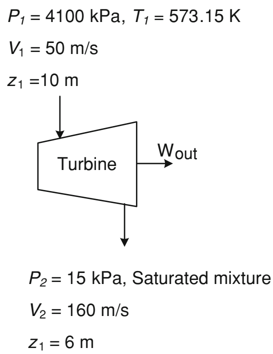
Fig. 6.2 Energy sources used in electricity production in the U.S. [12]

costs across great distances and power transformers can adjust the power by raising and lowering the voltage.

Renewable energy sources such as photovoltaics, wind, biomass, hydro, and geothermal can also provide clean and sustainable electricity. However, renewable energy sources are naturally variable, requiring energy storage or a hybrid system to accommodate daily and seasonal changes. One solution is to produce hydrogen through electrolysis by splitting of water and to use that hydrogen in a fuel cell to produce electricity during times of low power production or peak demand, or to use the hydrogen in fuel cell vehicles.

Example 6.1 Power production by an adiabatic steam turbine

A superheated steam at 4100 kPa and 300°C expands adiabatically in a steam turbine and exits at 15 kPa with a quality of $x = 0.9$. Velocity of the steam at the inlet is 50 m/s and at the exit 160 m/s. Elevation at the inlet is 10 m and at the exit 6 m. Estimate the power produced for the steam flow rate of 1kg/s.



Solution:
Assume: Steady-state adiabatic ($q_{\text{loss}} = 0$) process.

Steam flow rate: $\dot{m}_s = 1\,\text{kg/s}$
From Table F4:
Inlet conditions: $P_1 = 4100$ kPa and $T_1 = 300°\text{C}$, $v_1 = 50$ m/s, $z_1 = 10$ m, $H_1 = 2958.5$ kJ/kg,

Exit conditions: Saturated mixture of liquid and vapor water: (Table F3)
$P_{2,\text{sat}} = 15$ kPa, $T_{2,\text{sat}} = 54.0°\text{C}$, $H_{2\text{sat liq}} = 226.0$ kJ/kg,
$H_{2\text{sat vap}} = 2599.2$ kJ/kg, $x = 0.9$, $v_2 = 160$ m/s, $z_2 = 6$ m

$$H_{2\text{mix}} = (1-x)H_{\text{sat liq}} + xH_{\text{sat vap}} = (1-0.9)226\,\text{kJ/kg} + (0.9)2599.2\,\text{kJ/kg} = 2361.9\,\text{kJ/kg}$$

Energy balance: $W_{\text{out}} = \dot{m}\left(\Delta H + \dfrac{\Delta v^2}{2} + g\Delta z\right)$

$$\Delta H = H_2 - H_1 = (2361.9 - 2958.5)\text{kJ/kg} = -596.6\,\text{kJ/kg}$$

$$\Delta KE = \frac{v_2^2 - v_1^2}{2} = \left(\frac{160^2 - 50^2}{2}\right)\text{m}^2/\text{s}^2\left(\frac{\text{kJ/kg}}{1000\,\text{m}^2/\text{s}^2}\right) = 11.55\,\text{kJ/kg}$$

$$\Delta PE = g(z_2 - z_1)\left(\frac{\text{kJ/kg}}{1000\,\text{m}^2/\text{s}^2}\right) = 9.81(6-10)\text{m}^2/\text{s}^2\left(\frac{\text{kJ/kg}}{1000\,\text{m}^2/\text{s}^2}\right) = -0.04\,\text{kJ/kg}$$

$$W_{\text{out}} = \dot{m}\left(\Delta H + \frac{\Delta v^2}{2} + g\Delta z\right) = (1\text{kg/s})(-596.6 + 11.5 - 0.04)\text{kJ/kg} = \mathbf{-585.1\ kW}$$

Contribution of kinetic energy is less than 2%, and the contribution of potential energy is negligible. In practice, changes in kinetic and potential energies are assumed to be negligible.

6.3 Transmission of Energy

Electricity grids transmit and distribute power from production source to end user (see Fig. 6.3). Sources include coal or natural gas burning power plants as well as nuclear and solar power plants. A combination of substations, transformers, towers, and cables are used to maintain a constant flow of electricity at the required levels of voltage such as 110 or 220 V. Grids also have a predefined carrying capacity or load. New small-scale energy sources may be placed closer to the consumers so that less energy is lost during electricity distribution. New technology like superconductivity or improved power factor correction may also decrease the energy lost [1].

Crude oil is carried and distributed through long pipelines between the sources and refineries where it is fractioned to many different types of fuels, such as gasoline, kerosene, and fuel oil. Pipelines can also distribute the refined fractions of the crude oil to end users. Slurry pipelines are sometimes used to transport coal. Oil pipelines are made of steel or plastic tubes with inner diameter typically from

(a) (b)

Fig. 6.3 Transmission of energy: **a** an elevated section of the Alaska pipeline, **b** electric grid: pilons and cables distribute power

0.3 to 4 ft (0.1–1.2 m). For natural gas, pipelines are constructed of carbon steel and vary in size from 0.2 to 5 ft (0.06–1.5 m) in diameter, depending on the type of pipeline. The gas is pressurized by compressor stations. Most pipelines are buried at a typical depth of about 3–6 ft (0.9–1.8 m).

6.3.1 Distributed Energy Resources

Distributed energy resources are small power production or storage systems located close to the point of use. Distributed energy resources usually have higher efficiencies through cogeneration and may reduce emissions of carbon dioxide, because of their use of onsite renewable resources and low greenhouse gas fuels such as natural gas as seen in Fig. 6.4. Some distributed generation technologies, like photovoltaic and fuel cells, can generate electricity with no emissions or less emissions than that of central station fossil fuel-fired power plants. For distributed generation to enhance system level efficiency, improvements will be required in the performance of power-producing equipment, including advanced sensors and controls, energy storage, and heat exchangers to improve waste heat recovery and cycle efficiencies. Other advantages include fuel source flexibility, reduced transmission and distribution line losses, enhanced power quality and reliability, and more user control. Distributed generation permits consumers who are producing electricity for their own needs, to send their surplus electrical power back into the power grid [1].

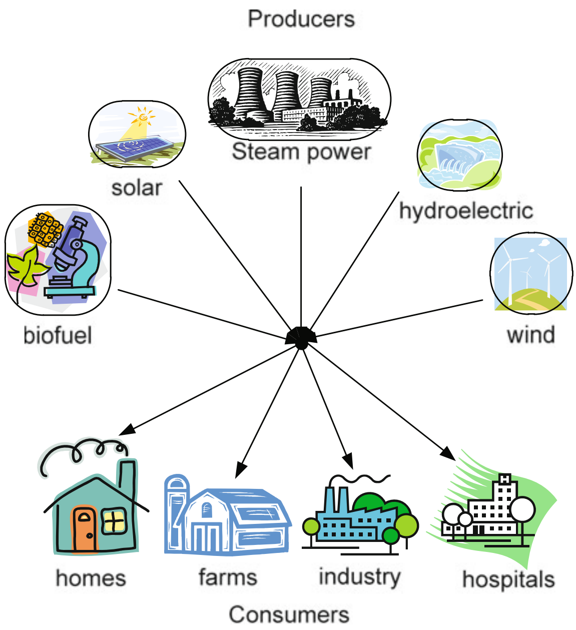


Fig. 6.4 Transition to distributed energy resources and use

6.4 Power Producing Engine Cycles

The systems used to produce a net power output are called *engines*. Most power producing engines operate with cyclic processes using a working fluid. Steam power plants use water as the working fluid. Actual engine cycles are complex to analyze. Therefore it is common to analyze the cycles by assuming that they operate without friction, heat losses, and other complexities [6, 32]. Such a cycle is known as the ideal engine. The analysis of ideal engines yields the major operating parameters controlling the cycle performance [4].

A *heat engine*, for example, converts heat to mechanical energy by bringing a working fluid from a high temperature state T_H to a lower temperature state T_C. Figure 6.5 shows typical pressure–volume *PV* and temperature-entropy *TS* diagrams of ideal engine cycles. On both the *PV* and *TS* diagrams, the area enclosing the process curves of a cycle represents the net work produced during the cycle, which is equivalent to the net heat transfer for the cycle. As seen in Fig. 6.5, The characteristics of cycles on a *TS* diagram are:

- Heat addition increases entropy,
- Heat rejection process decreases entropy,
- Isentropic (internally reversible and adiabatic) process takes place at constant entropy.

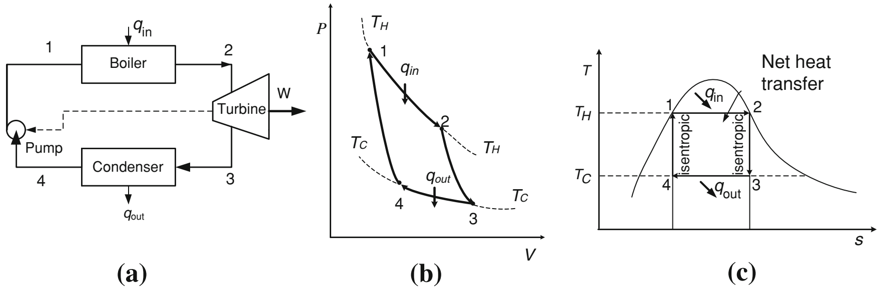


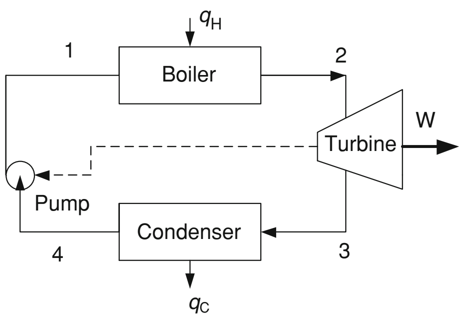
Fig. 6.5 Typical ideal engine cycles: **a** cyclic processes, **b** on a pressure–volume (*PV*) diagram, **c** on a temperature-entropy (*TS*) diagram

The area under the heat addition process on a *TS* diagram measures the total heat input, and the area under the heat rejection process measures the total heat output. The difference between these two areas represents the net heat transfer and also the net work output. Therefore, any modifications that improve the net heat transfer rate will also improve the net work output. Example 6.2 illustrates the analysis power output from a steam power plant [4, 6, 32].

A heat "source" heats the working fluid in the high temperature state. The working fluid generates work in the engine while transferring the remaining heat to the colder "sink" until it reaches a low temperature state. The working fluid usually is a liquid or gas. During the operation of an engine some of the thermal energy is converted into work and the remaining energy is lost to a heat sink mainly the general surroundings. Example 6.3 estimates the water mass flow rate for a given power output.

Example 6.2 Steam power production

A steam power production plant uses steams at 8200 kPa and 823.15 K. The turbine discharges the steam at 30 kPa. The turbine and pump operate reversibly and adiabatically. Determine the work produced for every kg steam produced in the boiler.



Solution:
Assume that the turbine and the pump operate reversibly and adiabatically; no pressure drop across condenser and boiler; only heat transfer occurs at condenser and boiler.

Steam flow rate: $\dot{m}_s = 1\,\text{kg/s}$
Steam data from Table F4:
Turbine inlet: $P_2 = 8200$ kPa; $T_2 = 823.15$ K; $H_2 = 3517.8$ kJ/kg;
$S_2 = 6.8646$ kJ/kg K

Turbine outlet: $P_3 = 30$ kPa; $T_3 = 342.27$ K, $V_4 = 0.001022$ m^3/kg (Table F3)
$H_{3\text{sat liq}} = 289.30$ kJ/kg, $H_{3\text{sat vap}} = 2625.4$ kJ/kg
$S_{3\text{sat liq}} = 0.9441$ kJ/kg K, $S_{3\text{sat vap}} = 7.7695$ kJ/kg K

For an ideal operation $S_2 = S_3 = 6.8646$. Since $S_3 < S_{3\text{sat vap}}$ the discharged steam is a mixture of liquid and vapor. Solve for fraction of vapor, x, using entropy balance for the exhaust of the turbine:

$$x_3 = \frac{S_2 - S_{3\text{sat liq}}}{S_{3\text{sat vap}} - S_{3\text{sat liq}}} = \frac{6.8646 - 0.9441}{7.7695 - 0.9441} = 0.867$$

$H_3 = 0.867(2625.4) + (1 - 0.867)(289.3) = 2315.8\,\text{kJ/kg},\ T_2 = 342.27\,\text{K(Saturated)}$
$H_1 = H_4 + (P_1 - P_4)\,V_4 = 289.3 + (8200 - 30)\,(0.001022) = 297.65$ kJ/kg
$q_{\text{out}} = (H_3 - H_4) = (2315.8 - 289.3)\,\text{kJ/kg} = 2026.5\,\text{kJ/kg}$ (absolute value)
$q_{\text{in}} = (H_2 - H_1) = (3517.8 - 297.65)$ kJ/kg $= 3220.2$ kJ/kg

Net work output for 1 kg/s steam: $W_{\text{out}} = \dot{m}_s(q_{\text{in}} - q_{\text{out}}) = \mathbf{1193.7\,kW}$ (Absolute value)

Example 6.3 Steam flow rate calculation in a power plant
A steam power plant output is 50 MW. It uses steam (stream 1) at 8200 kPa and 550°C. The discharged steam (stream 2) is saturated at 75 kPa. If the expansion in the turbine is adiabatic determine the steam flow rate.

Solution:
Assume that kinetic and potential energy are negligible, and the system is at steady state.
(a) Basis: 1 kg/s steam with the properties from the steam tables
Turbine inlet:
$H_1 = 3517.8$ kJ/kg, $S_1 = 6.8648$ kJ/kg K at $T_1 = 550$°C, $P_1 = 8200$ kPa (Table F4)
Turbine outlet:
$S_{2\text{sat vap}} = 7.3554$ kJ/kg K, $S_{2\text{sat liq}} = 1.2131$ kJ/kg K at $P_2 = 75$ kPa (saturated steam)
$H_{2\text{sat vap}} = 2663.0$ kJ/kg, $H_{2\text{sat liq}} = 384.45$ kJ/kg at (Table F3)

At isentropic conditions, we have $S_2 = S_1 < 7.3554$ kJ/kg K
Therefore, the discharged steam is wet steam:

x_s (the quality at isentropic operation): $x_s = \dfrac{6.8646 - 1.2131}{7.4570 - 1.2131} = 0.905$

The discharged steam enthalpy at isentropic conditions H_{2s} is

$$H_{2s} = H_{2\text{sat liq}}(1 - x_s) + H_{2\text{sat vap}} x_s = 384.45(1 - 0.905) + 2663(0.905) = 2446.8\,\text{kJ/kg}$$

The steam flow rate: $\dot{m} = \dfrac{-50000\,\text{kW}}{(H_{2s} - H_1)\text{kJ/kg}} = \mathbf{46.7\,kg/s}$

6.4.1 Carnot Cycle

A Carnot *heat engine* performs the conversion of heat to mechanical energy by bringing a working fluid from a high temperature state T_H to a lower temperature state T_C. Figure 6.5 shows a typical pressure–volume *PV* and temperature-entropy *TS* diagrams of ideal engine cycles. On both the *PV* and *TS* diagrams, the area enclosed by the process curves of a cycle represents the net heat transfer to be converted to mechanical energy by the engine.

Carnot cycle consists of four totally reversible processes shown in Fig. 6.5c:

- Process 1–2: Isothermal heat addition at constant temperature T_H.
- Process 2–3: Isentropic expansion at constant entropy $S_2 = S_3$.
- Process 3–4: isothermal heat rejection at constant temperature T_C.
- Process 4–1: isentropic compression at constant entropy $S_4 = S_1$.

From Fig. 6.5c, we can estimate the amounts of added and rejected heats per unit mass flow rate of a working fluid

$$q_\text{in} = T_H(S_2 - S_1) \tag{6.2}$$

$$q_\text{out} = T_C(S_4 - S_3) \tag{6.3}$$

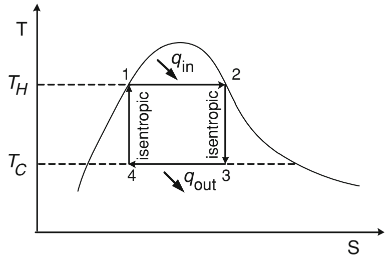
The net power output becomes

$$W_\text{out} = q_\text{in} - q_\text{out} \tag{6.4}$$

Example 6.4 illustrates the analysis of power output from a Carnot cycle.

Example 6.4 Power output from a Carnot cycle
A Carnot cycle uses water as the working fluid at a steady flow process. Heat is transferred from a source at 250°C and water changes from saturated liquid to saturated vapor. The saturated steam expands in a turbine at 10 kPa, and a heat of 1045 kJ/kg is transferred in a condenser at 10 kPa. Estimate the net power output of the cycle for a flow rate of 10 kg/s of the working fluid.

Solution:
Assumptions: Kinetic and potential energy changes are negligible.



Data from Table F3:
$\dot{m} = 10\,\text{kg/s}$
Turbine inlet:
$P_{sat} = 3977.6$ kPa, $T_\text{H} = 250°\text{C} = 523.15$ K,
Turbine outlet:
$T_\text{C} = T_\text{sat}$ (at 10 kPa) = 45.8°C = 318.8 K
Heat supplied is equivalent to the heat of vaporization at $T_\text{H} = 250°\text{C}$.
$H_{1\text{sat liq}} = 1085.8$ kJ/kg K, $H_{2\text{sat vap}} = 2800.4$ kJ/kg K, at $P_1 = P_2 = 3977.6$ kPa
$q_\text{in} = H_{2\text{sat vap}} - H_{2\text{sat liq}} = 1714.6$ kJ/kg, $q_\text{out} = 1045$ kJ/kg
Total Net power output of the cycle: $\dot{W}_\text{net} = \dot{m}(q_\text{in} - q_\text{out}) = \mathbf{6696.0\,kW}$

6.4.2 Rankine Cycle

The *Rankine cycle* converts heat into work and generates about 80% of all electric power used throughout the world. Figure 6.6 describes the main processes within the cycle. Common heat sources are the combustion of coal, natural gas, oil, and the fission of nuclear material. The Rankine cycle processes are:

- Process 1−2: The high pressure liquid enters a boiler where it is heated at constant pressure by an external heat source to become a dry saturated vapor.
- Process 2−3: The dry saturated vapor expands through a turbine, generating power. This decreases the temperature and pressure of the vapor, and some condensation may occur.
- Process 3−4: The wet vapor discharged from the turbine enters a condenser where it is condensed at a constant pressure to become a saturated liquid.
- Process 4−1: The water is pumped from low to high pressure to start a new cycle.

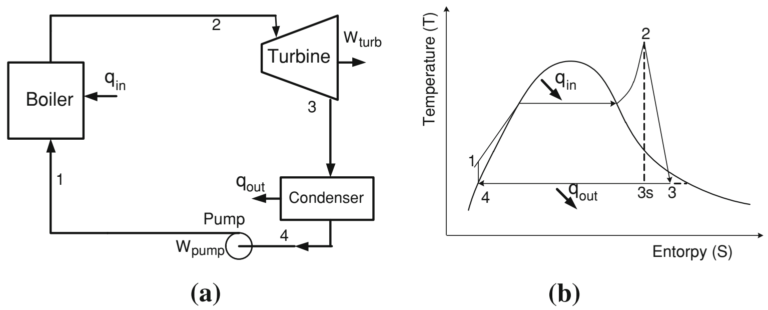


Fig. 6.6 **a** Schematic of Rankine cycle. **b** Rankine cycle processes on a *T* versus *S* diagram

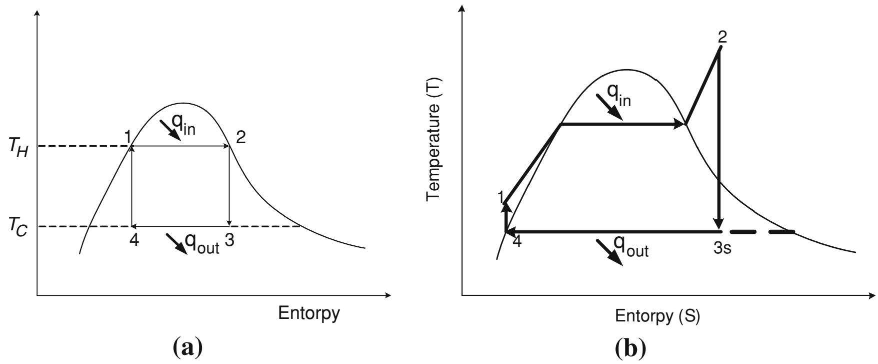


Fig. 6.7 **a** Carnot cycle. **b** Ideal Rankine cycle on a *T S* diagram, where on both the cycles pumps and turbines operate at constant entropy (isentropic operation)

The Rankine cycle is sometimes referred to as a practical Carnot cycle because in an ideal Rankine cycle the pump and turbine would be *isentropic* and produce no entropy and hence maximize the work output shown in Fig. 6.7 as the line 2–3s where the entropy remains constant. The main difference is that the heat addition (in the boiler) and heat rejection (in the condenser) are isobaric in the Rankine cycle and isentropic in the Carnot cycle.

6.4.2.1 Analysis of Ideal Rankine Cycle

The analyses of processes yield the following equations for a Rankine cycle: Pump power needed

$$\dot{W}_{p,\text{in}} = \dot{m}V_4(P_1 - P_4) \tag{6.5}$$

where $\dot{m}$ is the steam mass flow rate, V_4 is the specific volume at state 4 that is the saturated liquid water, and P_i is the pressures at state i. Enthalpy rate at state 1, H_1, is

$$\dot{m}H_1 = \dot{m}H_4 + \dot{W}_{p,\text{in}} \tag{6.6}$$

For isentropic process $S_1 = S_4$ and $S_2 = S_3$. The quality of the discharged wet steam, x_{3s}, shows the molar or mass fraction of vapor ($S_3 < S_{3\text{sat vap}}$):

$$x_{3s} = \frac{(S_3 - S_{3\text{sat liq}})}{(S_{3\text{sat vap}} - S_{3\text{sat liq}})} \tag{6.7}$$

where S_3 is the entropy at state 3, $S_{3\text{sat vap}}$, and $S_{3\text{sat liq}}$ are the entropy of saturated vapor and saturated liquid at state 3, respectively. Enthalpy rate of the wet steam at state 3 is

$$\dot{m}H_3 = \dot{m}[(1 - x_{3s})H_{3\text{sat liq}} + x_{3s}H_{3\text{sat vap}}] \tag{6.8}$$

where $H_{3\text{sat vap}}$ and $H_{3\text{sat liq}}$ are the saturated vapor and saturated liquid enthalpies at state 3. The rate of heat input, q_{in}, to the pressurized water in the boiler is

$$\dot{q}_{\text{in}} = \dot{m}(H_2 - H_1) \tag{6.9}$$

The discharged heat rate $\dot{q}_{\text{out}}$ at the condenser is

$$\dot{q}_{\text{out}} = \dot{m}(H_4 - H_3) \tag{6.10}$$

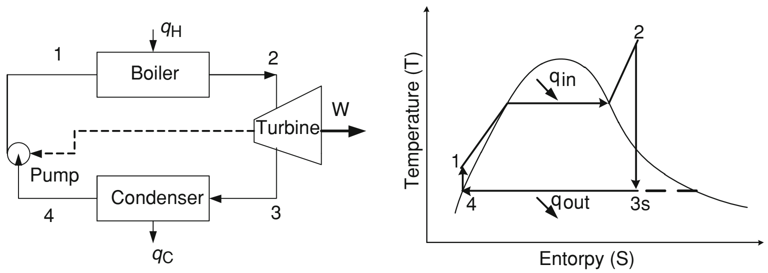
Net value of the work $\dot{W}_{\text{net}}$ produced is

$$\dot{W}_{\text{net}} = (\dot{q}_{\text{in}} - \dot{q}_{\text{out}}) \tag{6.11}$$

Performance of a steam turbine will be limited by the quality discharged steam. Discharged steam with a low quality may decrease the life of turbine blades and efficiency of the turbine. The easiest way to overcome this problem is by superheating the steam. Example 6.5 illustrates the analysis of an ideal Rankine cycle.

Example 6.5 Analysis of a simple ideal Rankine cycle

A steam power plant operates on a simple ideal Rankine cycle shown below. The turbine receives steam at 698.15 K and 4100 kPa, while the discharged steam is at 40 kPa. The mass flow rate of steam is 8.5 kg/s. Determine the net work output.



Solution:
Assume that the kinetic and potential energy changes are negligible.
$\dot{m}_s = 8.5 \text{ kg/s}$

$P_2 = P_1 = 4100$ kPa; $H_2 = 3272.3$ kJ/kg: $S_2 = 6.8450$ kJ/kg (Table F4)
Saturated steam properties at $P_3 = P_4 = 40$ kPa, $V_4 = 0.001022$ m^3/kg (Table F3)

$H_{3\text{sat vap}} = 2636.9$ kJ/kg; $H_4 = H_{3\text{sat liq}} = 317.65$ kJ/kg;
$S_{3\text{sat vap}} = 7.6709$ kJ/kg K; $S_{3\text{sat liq}} = 1.0261$ kJ/kg K
Basis: mass flow rate of 1 kg/s:

$$W_{p,\text{in}} = V_1(P_1 - P_4) = (0.001022)(4100 - 40)\left(\frac{1\text{kJ}}{1 \text{ kPa m}^3}\right) = 4.14\,\text{kJ/kg}$$

$$H_1 = H_4 + W_{p,\text{in}} = 321.79 \text{ kJ/kg}$$

Isentropic process $S_1 = S_4$ and $S_3 = S_2$. The quality of the discharged wet steam ($S_3 < S_{3\text{sat vap}}$):
$x_{3s} = (6.845 - 1.0262)/(7.6709 - 1.0261) = 0.875$
$H_3 = 317.65(1 - 0.875) + 2636.9 \times 0.875 = 2356.6 \text{ kJ/kg}$
$q_{\text{in}} = H_2 - H_1 = 2950.5 \text{ kJ/kg}$
$q_{\text{out}} = H_3 - H_4 = 2038.9 \text{ kJ/kg}$
With a steam flow rate of 8.5 kg/s, we have
$\dot{W}_{\text{net}} = \dot{m}(q_{\text{in}} - q_{\text{out}}) = 7748.6 \text{ kW} = \mathbf{7.75\,MW}$

6.4.3 Brayton Cycle

A gas turbine cycle relies on the *Brayton cycle* using air as the working fluid as shown in Fig. 6.8. An ideal Brayton cycle consists of the following processes:

- *Isentropic process*—Ambient air is drawn into the compressor.
- *isobaric process*—The compressed air then runs through a combustion chamber where fuel is burned, heating the air at a constant-pressure process.
- *isentropic process*—The heated, pressurized air then gives up its energy by expanding through a turbine (or series of turbines).
- *isobaric process*—Heat rejection to the surroundings.

Some of the electricity produced from the turbine is used to drive the compressor through a crankshaft arrangement. The gas turbine requires clean fuels such as natural gas or light fuel oil.

Actual Brayton cycle has the processes:

- Compression (adiabatic),
- Heat addition (isobaric),

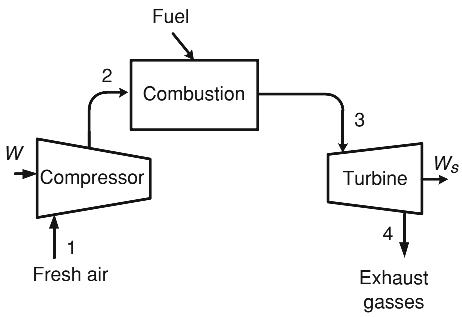


Fig. 6.8 Schematic of ideal Brayton cycle with processes of adiabatic compression, isobaric heat addition, adiabatic expansion, and isobaric heat rejection

- Expansion (adiabatic),
- Heat rejection (isobaric).

Since neither the compression nor the expansion can be truly isentropic, losses through the compressor and the expander may be considerable. Increasing the compression ratio increases the overall power output of a Brayton system. Intercooling the working fluid decreases the amount of work needed for the compression stage overall and increases the fuel consumption of the combustion chamber. To increase the power output for a given compression ratio, air expands through a series of turbines and then is passed through a second combustion chamber before expanding to ambient pressure [4, 7].

6.4.4 Stirling Engine

A Stirling engine is a heat engine operating by cyclic compression and expansion of the working fluid at different temperature levels such that there is a net conversion of heat energy to mechanical work. The working fluid is mainly air although other gases can also be used. The Stirling engine is highly efficient compared to steam engines and can use almost any heat source [17, 28]. The Stirling engine is classified as an external combustion engine, as all heat transfers to and from the working fluid take place through the engine wall. The engine cycle consists of compressing gas, heating the gas, expanding the hot gas, and finally cooling the gas before repeating the cycle. Its practical use is largely confined to low power domestic applications.

6.4.5 *Combined Cycles*

A combined cycle power plant uses the Brayton cycle of the gas turbine with the Rankine cycle of a heat recovery steam generator. The combined cycle plants are designed in a variety of configurations composed of a number of gas turbines followed by a steam turbine. They generate power by burning natural gas in a gas turbine and use residual heat to generate additional electricity from steam [4, 21].

Coal gasification produces a fuel gas that is capable of being used in the gas turbine. By integrating coal gasification with gas turbine and steam cycles, a low pollutant emission can be achieved while using coal. A potential additional advantage of the integrated gasification combined cycle is the capability of capturing carbon dioxide from the fuel gas and making it ready for high-pressure pipeline transportation to a carbon sequestration site.

6.5 Improving the Power Production in Steam Power Plants

Improvements on power plant operations may increase efficiency and power output while reducing the fuel consumption. The modifications for improvements aim at increasing the average temperature at which heat is transferred to the steam in the boiler and decrease the average temperature at which heat is removed in the condenser [6, 9, 20, 27]. Some common modifications in steam power production are summarized in the following sections.

6.5.1 *Modification of Operating Conditions of the Condenser and Boiler*

Superheating the steam to high temperature increases the temperature at which the heat flows into the boiler and increases the power output and quality of the discharged steam. Figure 6.9 shows the effects of superheating the steam to higher temperatures and reducing the condenser pressure on the ideal Rankine cycle on a *TS* diagram. The area enclosed by the process curve "1′–2′–3′–4′" is larger than that of the area for "1–2–3–4" and represents the net work output increase of the cycle under higher boiler temperature and lower condenser pressure. The operating pressures may be as high as 30 MPa (4500 psia) in modern steam power plants operating at supercritical pressures ($P > 22.09$ MPa). By metallurgical constraints, the temperature of steam is limited. The temperature at the turbine inlet may be as high as 620°C [7].

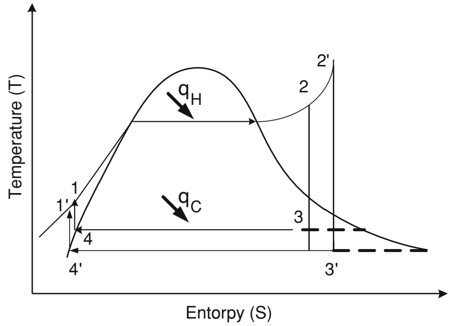


Fig. 6.9 Effects of superheating the steam to higher temperatures and reducing the condenser pressure on an ideal Rankine cycle

6.5.2 Reheating the Steam

Superheating the steam to high temperatures enables the expansion of the steam in various stages instead of a single expansion process. Mainly, reheating increases the power output and the steam quality to protect the material. Figure 6.10 shows a typical reheat Rankine cycle. In an ideal reheat Rankine cycle with two-stage expansion, for example, the steam is expanded to an intermediate pressure isentropically in the high-pressure turbine section, and sent to the boiler to be reheated. In the low-pressure turbine section, the reheated steam is expanded to the condenser operating pressure. Example 6.6 illustrates a simple analysis of ideal reheat Rankine cycle.

Example 6.6 Simple reheat Rankine cycle in a steam power plant
A simple ideal reheat Rankine cycle is used in a steam power plant shown in Fig. 6.10. Steam enters the turbine at 9000 kPa and 823.15 K and leaves at 4350 kPa and 698.15 K. The steam is reheated at constant pressure to 823.15 K. The discharged steam from the low-pressure turbine is at 10 kPa. The net power output of the turbine is 40 MW. Determine the mass flow rate of steam.

Solution:
Assume that the kinetic and potential energy changes are negligible, and this is a steady process.

Consider Fig. 6.10.
Data: Steam data from Table F3 and Table F4
$V_1 = 0.00101$ m^3/kg, $P_3 = 9000$ kPa, $H_3 = 3509.8$ kJ/kg, $S_3 = 6.8143$ kJ/kg
$P_6 = 10$ kPa
$T_4 = 698.15$ K, $P_4 = 4350$ kPa, $H_4 = 3268.5$ kJ/kg, $S_3 = S_4 = 6.8143$ kJ/kg
$T_5 = 823.15$ K, $P_5 = 4350$ kPa, $H_5 = 3555.2$ kJ/kg, $S_5 = S_6 = 7.1915$ kJ/kg

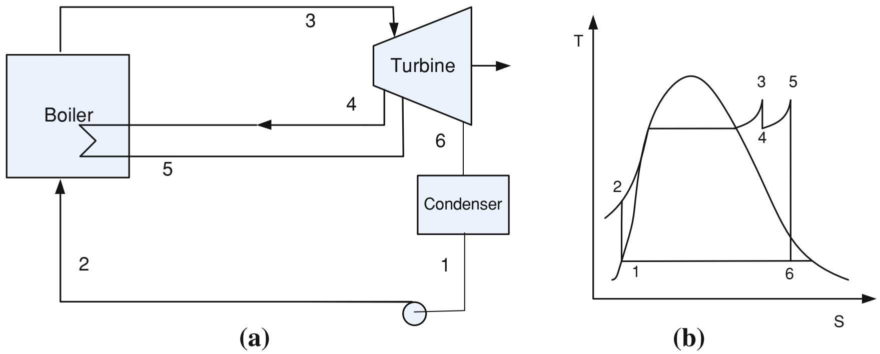


Fig. 6.10 **a** Ideal reheat Rankine cycle. **b** T versus S diagram for the reheat Rankine cycle

Saturated vapor and liquid data:
$H_{6\text{sat vap}} = H_{1\text{sat vap}} = 2584.8$ kJ/kg, $H_{1\text{sat liq}} = H_{6\text{sat liq}} = 191.81$ kJ/kg (Table F3)
$S_{6\text{sat vap}} = 8.1511$ kJ/kg K, $S_{6\text{sat liq}} = 0.6493$ kJ/kg K
Based on $\dot{m} = 1\,\text{kg/s}$ steam flow rate:

$$W_{p,\text{in}} = V_1(P_2 - P_1) = 0.00101(9000 - 10)\left(\frac{1\text{kJ}}{1\text{ kPa m}^3}\right) = 9.08\text{ kJ/kg}$$

$$H_2 = H_1 + W_{p,\text{in}} = 200.9\text{ kJ/kg}$$

Because this is an isentropic process $S_5 = S_6$ and $S_1 = S_2$. We estimate the quality of the discharged wet steam ($S_6 < S_{6\text{sat vap}}$) after passing through the turbine:
$x_{6s} = (7.1915 - 0.6493)/(8.1511 - 0.6493) = 0.872$
$H_6 = 191.81(1 - 0.872) + 2584.8(0.872) = 2278.7\text{ kJ/kg}$

Heat interactions:
$q_{23,\text{in}} = H_3 - H_2 = 3308.9\text{ kJ/kg}$
$q_{45,\text{in}} = H_5 - H_4 = 286.7\text{ kJ/kg}$
$q_{\text{out}} = H_1 - H_6 = 2086.9\,\text{kJ/kg}$
$q_{\text{in}} = q_{23,\text{in}} + q_{45,\text{in}} = 3595.6\,\text{kJ/kg}$
$\dot{W}_{\text{out}} = \dot{m}(q_{\text{in}} - q_{\text{out}}) - \dot{m}(3595.5 - 2086.9)\text{kJ/kg} = 40000\,\text{kW}$
$\dot{m} = \mathbf{26.5\ kg/s}$

In this ideal reheat Rankine cycle, the expanded steam from the first part of the high-pressure section is reheated in the boiler until it reaches the boiler exit temperature. The reheated steam is expanded through the turbine to the condenser conditions. The reheating decreases the moisture within the discharged steam.

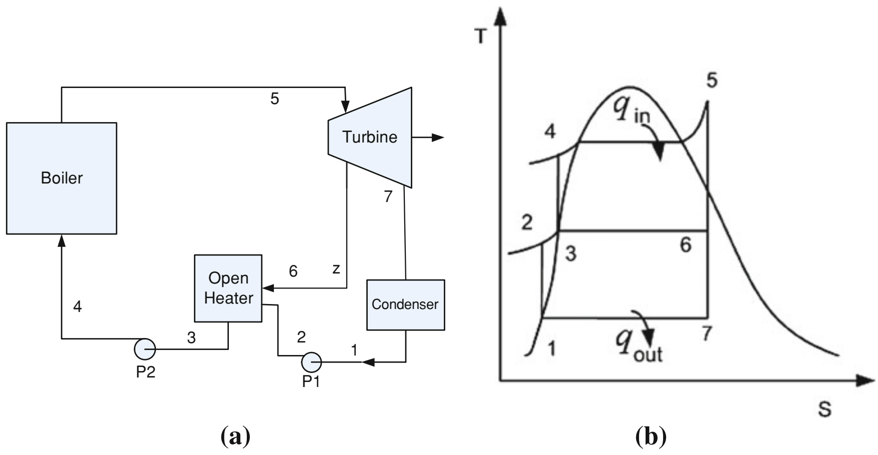


Fig. 6.11 **a** Ideal regenerative Rankine cycle. **b** Temperature *T* versus entropy *S* diagram for ideal regenerative Rankine cycle. Here P1 and P2 show the circulation pumps

6.5.3 Regeneration

Increasing the boiler water feed temperature by using the expanding steam is possible in a regenerative cycle. Figure 6.11 shows a typical regenerative Rankine cycle. Steam extracted at intermediate pressures from the turbine is used to heat the boiler water feed. The steam at stage 3 leaves the condenser as a saturated liquid at the condenser operating pressure by adjusting the fraction of steam extracted from the turbine. Regeneration helps deairate the water and control the discharged steam flow rate. Example 6.7 illustrates a simple analysis of ideal regenerative Rankine cycle.

Example 6.7 Power output of ideal regenerative Rankine cycle
A steam power plant is using an ideal regenerative Rankine cycle shown in Fig. 6.11. Steam enters the high-pressure turbine at 8200 kPa and 773.15 K, and the condenser operates at 20 kPa. The steam is extracted from the turbine at 350 kPa to heat the feed water in an open heater. The water is a saturated liquid after passing through the feed water heater. Determine the net power output of the cycle.

Solution**:**
Assume that the kinetic and potential energy changes are negligible, and this is a steady-state process.

Consider Fig. 6.11.
Basis: steam flow rate is 1 kg/s
The steam data are from Table F_3 and Table F_4:

$V_1 = 0.001017$ m^3/kg, $V_3 = 0.001079$ m^3/kg,
$T_5 = 773.15$ K, $P_5 = 8200$ kPa, $H_5 = 3396.4$ kJ/kg, $S_5 = 6.7124$ kJ/kg

$P_1 = P_7 = 20$ kPa,
$H_{7\text{sat vap}} = H_{1\text{sat vap}} = 2609.9$ kJ/kg, $H_{7\text{sat liq}} = H_{1\text{sat liq}} = 251.45$ kJ/kg,
$S_{7\text{sat vap}} = 7.9094$ kJ/kg K, $S_{7\text{sat liq}} = 0.8321$ kJ/kg K

$P_2 = P_3 = 350$ kPa,
$H_{6\text{sat liq}} = H_{3\text{sat liq}} = 584.27$ kJ/kg, $H_{6\text{sat vap}} = H_{3\text{sat vap}} = 2731.50$ kJ/kg
$S_{3\text{sat liq}} = 1.7273$ kJ/kg K, $S_{3\text{sat vap}} = 6.9392$ kJ/kg K

In this ideal regenerative Rankine cycle, the steam extracted from the turbine heats the water from the condenser, and the water is pumped to the boiler. Sometimes, this occurs in several stages. The condensate from the feed water heaters is throttled to the next heater at lower pressure. The condensate of the final heater is flashed into the condenser.

$$W_{p1} = V_1(P_2 - P_1) = 0.001017(350 - 20)\left(\frac{1\,\text{kJ}}{1\,\text{kPa}\,\text{m}^3}\right) = 0.335\,\text{kJ/kg}$$
$$H_2 = H_1 + W_{p1} = 252.78\,\text{kJ/kg}$$
$$W_{p2} = V_3(P_4 - P_3) = 0.001079(8200 - 350)\left(\frac{1\,\text{kJ}}{1\,\text{kPa}\,\text{m}^3}\right) = 8.47\,\text{kJ/kg}$$
$$H_4 = H_3 + W_{p2} = 592.74\,\text{kJ/kg}$$

Because this is an isentropic process, $S_5 = S_6 = S_7$. We estimate the quality of the discharged wet steam at states 6 ($S_5 < S_{6\text{sat vap}}$) and 7 ($S_5 < S_{7\text{sat vap}}$):

$$x_6 = \frac{6.7124 - 1.7273}{6.9392 - 1.7273} = 0.956$$
$$H_6 = 584.27(1 - 0.956) + 2731.50(0.956) = 2638.0\,\text{kJ/kg}$$
$$x_7 = \frac{6.7124 - 0.8321}{7.9094 - 0.8321} = 0.83$$
$$H_7 = 252.45(1 - 0.83) + 2609.9(0.83) = 2211.18\,\text{kJ/kg K}$$

The fraction of steam extracted is estimated from the energy balance:
$\dot{m}_6 H_6 + \dot{m}_2 H_2 = \dot{m}_3 H_3$
In terms of the mass fraction $z = \dot{m}_6/\dot{m}_3$, the energy balance becomes
$zH_6 + (1 - z)H_2 = H_3$

The mass fraction: $z = \dfrac{H_3 - H_2}{H_6 - H_2} = 0.139$
$q_{\text{in}} = (H_5 - H_4) = 2803.66\,\text{kJ/kg}$
$q_{\text{out}} = (1 - z)(H_7 - H_1) = 1686.52\,\text{kJ/kg}$
$W_{\text{net}} = (q_{\text{in}} - q_{\text{out}}) = \mathbf{1117.13\,kJ/kg}$

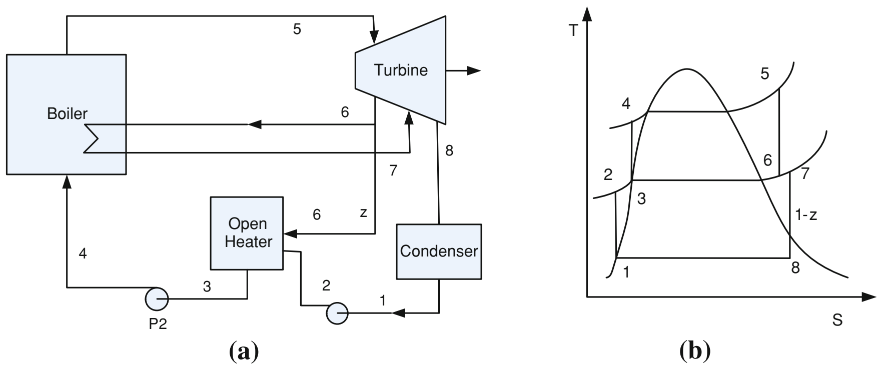


Fig. 6.12 **a** Schematic of ideal reheat regenerative Rankine cycle. **b** *T-S* diagram of the cycle

6.5.4 Reheat–Regenerative Rankine Cycle

In *reheat–regenerative Rankine cycle*, shown in Fig. 6.8, the part of steam extracted from the turbine heats the water from the condenser, and the remaining part is reheated in the boiler. Example 6.8 illustrates a simple analysis of reheat–regenerative Rankine cycle.

Example 6.8 Ideal reheat–regenerative cycle
A steam power plant is using an ideal reheat regenerative Rankine cycle. Steam enters the high pressure turbine at 9000 kPa and 773.15 K and leaves at 850 kPa. The condenser operates at 10 kPa. Part of the steam is extracted from the turbine at 850 kPa to heat the water in an open heater, where the steam and liquid water from the condenser mix and direct contact heat transfer takes place. The rest of the steam is reheated to 723.15 K, and expanded in the low pressure turbine section to the condenser pressure. The water is a saturated liquid after passing through the water heater and is at the heater pressure. The flow rate of steam is 32.5 kg/s. Determine the power produced.

Solution:
Assume negligible kinetic and potential energy changes, and that this is a steady-state process.

Consider Fig. 6.12.
The steam data from Table F3 and Table F4:
$P_5 = 9000$ kPa, $H_5 = 3386.8$ kJ/kg, $S_5 = 6.6600$ kJ/kg K, $T_5 = 773.15$ K
$P_1 = P_8 = 10$ kPa, $H_{8\text{sat vap}} = 2584.8$ kJ/kg, $H_{8\text{sat liq}} = 191.83$ kJ/kg,
$V_1 = 0.00101$ m^3/kg
$S_{8\text{sat vap}} = 8.1511$ kJ/kg K, $S_{8\text{sat liq}} = 0.6493$ kJ/kg K

$P_3 = 850$ kPa, $H_{3\text{sat liq}} = 732.03$ kJ/kg, $H_{3\text{sat vap}} = 2769.90$ kJ/kg,
$V_3 = 001079$ m^3/kg
$P_7 = 850$ kPa, $H_7 = 3372.7$ kJ/kg, $S_7 = 7.696$ kJ/kg K, $T_7 = 723.15$ kPa
S_5 and $P_6 = 850$ kPa $\rightarrow$ $T_6 = 450.0$ K, $H_6 = 2779.58$ kJ/kg

Work and enthalpy estimations for a unit mass flow rate of steam yield:

$$W_{p1} = V_1(P_2 - P_1) = 0.00101(850 - 10)\left(\frac{1\,\text{kJ}}{1\,\text{kPa}\,\text{m}^3}\right) = 0.848\,\text{kJ/kg}$$
$$H_2 = H_1 + W_{p1} = 192.68\,\text{kJ/kg}$$
$$W_{p2} = V_3(P_4 - P_3) = 0.001079(9000 - 850)\left(\frac{1\,\text{kJ}}{1\,\text{kPa}\,\text{m}^3}\right) = 90.046\,\text{kJ/kg}$$
$$H_4 = H_3 + W_{p2} = 7410.07\,\text{kJ/kg}$$

Because this is an isentropic process, $S_5 = S_6$ and $= S_7 = S_8$, we estimate the quality of the discharged wet steam at state 8 ($S_7 < S_{8\text{sat vap}}$):
$$x_8 = \frac{7.696 - 0.6493}{8.1511 - 0.6493} = 0.94$$
$$H_8 = 191.83(1 - 0.94) + 2584.8(0.94) = 2439.63\,\text{kJ/kg}$$
The fraction of steam extracted is estimated from the energy balance $\dot{m}_6 H_6 + \dot{m}_2 H_2 = \dot{m}_3 H_3$.
In terms of the mass fraction $z = \dot{m}_6/\dot{m}_3$, the energy balance becomes: $zH_6 + (1 - z)H_2 = H_3$.
The mass fraction is

$$z = \frac{H_3 - H_2}{H_6 - H_2} = \frac{732.03 - 192.68}{2779.58 - 192.68} = 0.208$$

The turbine work output with $\dot{m} = 1\,\text{kg/s}$ working fluid is:
$$q_{\text{in}} = [(H_5 - H_4) + (1 - z)(H_7 - H_6)] = 3115.18\,\text{kW}$$
$$q_{\text{reheat}} = z(H_7 - H_6) = 593.12\,\text{kW}$$
$$q_{\text{out}} = (1 - z)(H_8 - H_1) = 1779.14\,\text{kW}$$
For steam flow rate of 36.5 kg/s:
$$\dot{W}_{\text{net}} = \dot{m}_s(q_{\text{in}} - q_{\text{out}}) = \mathbf{48{,}764\,kW} = \mathbf{48.8\,MW}$$

6.6 Geothermal Power Plants

Figure 6.13 shows a schematic of a geothermal power plant. Geothermal power comes from heat energy buried beneath the surface of the earth. There are three types of geothermal power plants:

- *Dry Steam Power Plants*: The geothermal steam goes directly to a turbine, where it expands and produces power. The expanded steam is injected into the geothermal well.

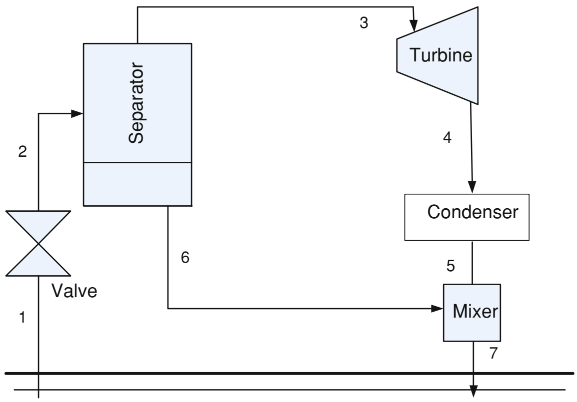


Fig. 6.13 Schematic of a geothermal plant

- *Flash Steam Power Plants*: Geothermal fluids above 360°F (182°C) can be flashed in a tank at low pressure causing some of the fluid to rapidly vaporize. The vapor then expands in a turbine.
- *Binary-Cycle Power Plants*: Moderate-temperature geothermal fluids between 85 and 170°C are common. The term "binary" refers to dual-fluid systems, wherein hot geothermal brine is pumped through a heat exchange network to transfer its energy to a working fluid driving a power train. A hot geothermal fluid and a suitable working fluid with a much lower boiling point then the geothermal fluid pass through a heat exchanger. The vaporized working fluid drives the turbines; no working fluid is emitted into the atmosphere. The working fluids may be isobutene, isopentane, n-pentane, or ammonia.

At temperatures below about 200°C, binary power systems are favored for relative cost effectiveness. In general, above about 200°C, flashing geothermal fluids to produce steam and directly driving turbine/generator is preferred. Example 6.9 illustrates a simple analysis of a steam power plant using a geothermal source [4, 10].

Example 6.9 A steam power plant using a geothermal energy source

A steam power plant is using a geothermal energy source. The geothermal source is available at 220°C and 2319.8 kPa with a flow rate of 200 kg/s. The hot water goes through a valve and a flash drum. Steam from the flash drum enters the turbine at 550 kPa and 428.62 K. The discharged steam from the turbine has a quality of $x_4 = 0.96$. The condenser operates at 10 kPa. The water is a saturated liquid after passing through the condenser. Determine the work output of turbine.

Solution:

Assume: The kinetic and potential energy changes are negligible, and this is a steady-state process.

The steam data from Table F3 and Table F4:
$T_1 = 493.15$ K, $P_1 = 2319.8$ kPa, $H_1 = H_2 = 943.7$ kJ/kg, $S_1 = 2.517$ kJ/kg K,
$T_3 = 428.62$ K, $P_3 = 550$ kPa, $H_3 = 2751.7$ kJ/kg, $S_3 = 6.787$ kJ/kg K (saturated),
$H_{3\text{sat vap}} = 2551.7$ kJ/kg, $H_{3\text{sat liq}} = 655.80$ kJ/kg, $S_{3\text{sat vap}} = 6.787$ kJ/kg K,
$S_{3\text{sat liq}} = 1.897$ kJ/kg K
$P_4 = 10$ kPa, $H_{4\text{sat vap}} = 2584.8$ kJ/kg, $H_{4\text{sat liq}} = 191.8$ kJ/kg

In this geothermal power plant, the hot water is flashed and steam is produced. This steam is used in the turbine.

The rate of vapor is estimated from the quality at state 2. The fraction of steam after flashing is:

$$x_2 = \frac{943.7 - 655.8}{2751.7 - 655.8} = 0.159$$

$$S_2 = (1 - 0.159)1.897 + 0.159(6.787) = 2.6756$$

The steam flow rate is: $\dot{m}_3 = x_2(\dot{m}_1) = 0.159(200) = 31.84\,\text{kg/s}$
From the mass balance around the flash drum, we have $\dot{m}_6 = \dot{m}_1 - \dot{m}_3 = 168.15\,\text{kg/s}$

The discharged steam has the quality of: $x_4 = 0.96$
$H_4 = (1-0.96)H_{4\text{sat liq}} + (0.96)H_{4\text{sat vap}} = 2489.08$ kJ/kg

From the flash drum at state 6, we have
$\dot{W}_{\text{net}} = \dot{m}_3(H_4 - H_3) = \mathbf{-8363.71\,kW}$

6.7 Cogeneration

Figure 6.14 shows a typical cogeneration plant. Cogeneration plant produces electric power and process heat from the same heat source. This may lead to the utilization of more available energy and the reduction of waste heat. A cogeneration plant, for example, may use the waste heat from Brayton engines, typically for hot water production or for space heating. The process heat in industrial plants usually needs steam at 500–700 kPa, and 150–200°C. The steam expanded in the turbine to the process pressure is used as process heat. Cycles making use of cogeneration may be an integral part of large processes where the energy of the expanded steam from the turbine at intermediate pressure may be fully utilized in producing electricity and process heat simultaneously. The *utilization factor* for a cogeneration plant is the ratio of the energy used in producing power and process heat to the total energy input. Examples 6.10 and 6.11 illustrate simple analyses of energy output in cogeneration plants [4, 7].

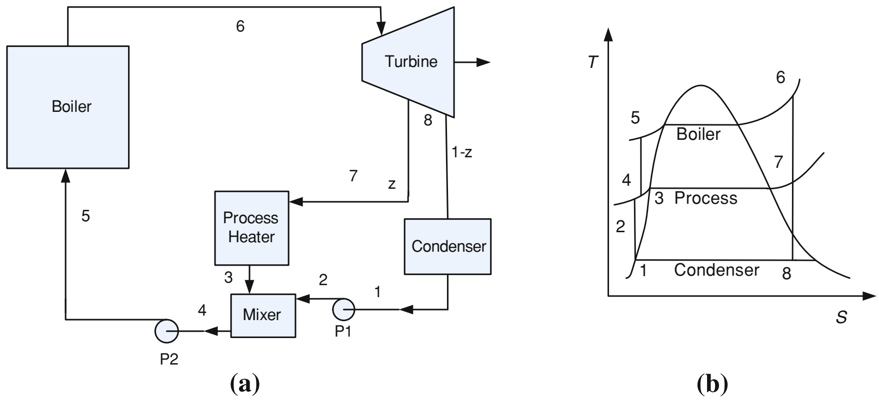


Fig. 6.14 **a** Schematic of ideal cogeneration plant. **b** *TS* diagram

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Example 6.10 Energy output in a cogeneration plant
A cogeneration plant is using steam at 8200 kPa and 773.15 K (see Fig. 6.14). One-fourth of the steam is extracted at 700 kPa from the turbine for cogeneration. After it is used for process heat, the extracted steam is condensed and mixed with the water output of the condenser. The rest of the steam expands from 8200 kPa to the condenser pressure of 10 kPa. The steam flow rate produced in the boiler is 60 kg/s. Determine the work output and process heat produced.

Solution:
Assume that the kinetic and potential energy changes are negligible, and this is a steady-state process.
Consider Fig. 6.14.
The steam data from Table F3 and Table F4:
$\dot{m} = 60\,\mathrm{kg/s}, z = 0.25$
$P_1 = P_8 = 10$ kPa, $H_{1\mathrm{sat\ vap}} = 2584.8$ kJ/kg, $H_{1\mathrm{sat\ liq}} = 191.83$ kJ/kg,
$V_1 = 0.00101$ m^3/kg, $S_{1\mathrm{sat\ vap}} = 8.1511$ kJ/kg K, $S_{1\mathrm{sat\ liq}} = 0.6493$ kJ/kg K

$P_3 = P_7 = P_2 = P_4 = 700$ kPa, $H_3 = 697.06$ kJ/kg, $S_3 = 1.9918$ kJ/kg K
Table F_4:
$P_6 = 8200$ kPa, $T_6 = 773.15$ K, $H_6 = 3396.4$ kJ/kg, $S_6 = 6.7124$ kJ/kg K

In this cogeneration cycle, the steam extracted from the turbine is used as process heat. The liquid condensate from the process heat is combined with the output of the condenser.
Basis: mass flow rate = 1 kg/s

$$W_{p1} = V_1(P_2 - P_1) = 0.00101(700 - 10)\left(\frac{1\,\mathrm{kJ}}{1\,\mathrm{kPa\,m^3}}\right) = 0.697\,\mathrm{kJ/kg}$$

$$H_2 = H_1 + W_{p1} = 191.83 + 0.697 = 192.53\,\mathrm{kJ/kg}$$

From the energy balance around the mixer, we have $\dot{m}_3/\dot{m}_6 = 0.25$

$\dot{m}_6 = \dot{m}_4 = 60\,\mathrm{kg/s}$, $\dot{m}_3 = \dot{m}_7 = 15\,\mathrm{kg/s}$, $\dot{m}_8 = \dot{m}_1 = 0.75(60) = 45.0\,\mathrm{kg/s}$
$\dot{m}_4 H_4 = \dot{m}_2 H_2 + \dot{m}_3 H_3$
$H_4 = [45(192.53) + 15(697.06)]/60 = 318.66$ kJ/kg
$T_4 = 349.15$ K, $V_4 = 0.001027$ kg/m^3
$W_{p2} = V_4(P_5 - P_4) = 0.001027(8200 - 700)\left(\frac{1\,\mathrm{kJ}}{1\,\mathrm{kPa\,m^3}}\right) = 7.70\,\mathrm{kJ/kg}$
$H_5 = H_4 + W_{p2} = 326.36\,\mathrm{kJ/kg}$
Isentropic processes: $S_6 = S_7 = S_8 = 6.7124$ and $P_7 = 700$ kPa,
$H_7 = 2765.68$ kJ/kg.

We estimate the quality of the discharged wet steam at state 8:
$$x_8 = \frac{6.7124 - 0.6493}{8.1511 - 0.6493} = 0.808$$
$$H_8 = 191.83(1 - 0.808) + 2584.80(0.808) = 2125.87\,\mathrm{kJ/kg}$$

The energy balance yields the fraction of steam extracted
$$\dot{W}_{\mathrm{total}} = \dot{m}_6(H_7 - H_6) + \dot{m}_8(H_8 - H_7) = -66634.44\,\mathrm{kW}$$
$$\sum \dot{W}_{pi} = \dot{m}_1 W_{p1} + \dot{m}_4 W_{p2} = 493.51\,\mathrm{kW}$$

The net work output:
$$\dot{W}_{\mathrm{net}} = \dot{W}_{\mathrm{total}} - \sum \dot{W}_{pi} = \mathbf{-66140.93\,kW}$$
$$\dot{q}_{\mathrm{process}} = \dot{m}_7(H_7 - H_3) = \mathbf{31029.3\,kW}$$

Example 6.11 Estimation of process heat in a cogeneration plant
A cogeneration plant uses steam at 900 psia and 1000°F to produce power and process heat. The steam flow rate from the boiler is 16 lb/s. The process requires steam at 70 psia at a rate of 3.2 lb/s supplied by the expanding steam in the turbine with a value of $z = 0.2$. The extracted steam is condensed and mixed with the water output of the condenser. The remaining steam expands from 70 psia to the condenser pressure of 3.2 psia. Determine the rate of process heat.

Solution:
Assume that the kinetic and potential energy changes are negligible, and this is a steady-state process.

Consider Fig. 6.14. The steam data from Table F1 and Table F2:
$\dot{m}_6 = 16\,\mathrm{lb/s}$, $z = \dot{m}_3/\dot{m}_6 = 0.2$, $\dot{m}_3 = 3.2\,\mathrm{lb/s}$
$P_1 = P_8 = 3.2$ psia, $H_{1\mathrm{sat\ vap}} = 1123.6$ Btu/lb, $H_{1\mathrm{sat\ liq}} = 111.95$ Btu/lb
$V_1 = 0.01631$ ft^3/lb
$S_{1\mathrm{sat\ vap}} = 0.2051$ Btu/lb R, $S_{1\mathrm{sat\ liq}} = 1.8810$ Btu/lb R
$P_3 = 70$ psia, $H_3 = 272.74$ Btu/lb, (Saturated)
$P_6 = 900$ psia, $H_6 = 1508.5$ Btu/lb, $S_6 = 1.6662$ Btu/lb R, $T_6 = 1000$°F

In this cogeneration cycle, the steam extracted from the turbine is used in process heat. The liquid condensate from the process heat is combined with the output of the condenser.

Basis: mass flow rate = 1 lb/s

$W_{p1} = V_1(P_2 - P_1) = 0.01631(70 - 3.2)\left(\dfrac{1\,\text{Btu}}{5.4039\,\text{psia ft}^3}\right) = 0.20\,\text{Btu/lb}$

$H_2 = H_1 + W_{p1} = 111.95 + 0.20 = 112.15\,\text{Btu/lb}$

From the energy balance around the mixer, we have z = 0.2:

$$\dot{m}_4 H_4 = \dot{m}_2 H_2 + \dot{m}_3 H_3 \quad H_4 = (\dot{m}_2 H_2 + \dot{m}_3 H_3)/\dot{m}_4$$

Basis: 1 lb/s then $\dot{m}_2 = \dot{m}_1 = 0.8\,\text{lb/s}$, $\dot{m}_3 = 0.2$ lb/s, $\dot{m}_4 = 1$ lb/s

$H_4 = [0.8(112.18) + 0.2(272.74]/1 = 144.29$ Btu/lb $\rightarrow S_4 = 0.2573$ Btu/lb R

$T_4 = 635.87$ R

$W_{p2} = V_4(P_5 - P_4) = 0.0175(900 - 70)\left(\dfrac{1\,\text{Btu}}{5.4039\,\text{psia ft}^3}\right) = 2.7$ Btu/lb

$H_5 = H_4 + W_{p2} = 147.0$ Btu/lb

Because these are isentropic processes, $S_6 = S_{7s} = S_{8s} = 1.6662$ Btu/lb R $P_7 = 70$ psia, $H_{7s} = 1211.75$ Btu/lb.

Quality of the discharged wet steam at state 8s is:

$x_{8s} = \dfrac{1.6662 - 0.2051}{1.8810 - 0.2051} = 0.871$

$H_{8s} = 111.95(1 - 0.871) + 1123.6(0.871) = 993.93$ Btu/lb

The steam quality at state 8: $x_8 = \dfrac{993.9 - 111.95}{1123.60 - 111.95} = 0.87$

Process heat: $\dot{q}_{\text{process}} = \dot{m}_3(H_7 - H_3) = \mathbf{3004.8\,Btu/s}$

6.8 Nuclear Power Plants

Nuclear power is a method in which steam is produced by heating water through a process called *nuclear fission*. Nuclear fission is a nuclear reaction in which the nucleus of an atom splits into smaller parts, often producing free neutrons and photons in the form of *gamma rays* (γ). *Gamma rays* are electromagnetic radiation of frequencies above 10^{19} Hz, and therefore have energies above 100 keV and wavelength less than 10 pm. In a nuclear power plant, a reactor contains a core of nuclear fuel, primarily uranium. When atoms of uranium fuel are hit by neutrons, they fission (split) releasing heat and more neutrons. Under controlled conditions, these neutrons can strike and split more uranium atoms.

Typical fission releases about two hundred million eV of energy (1 eV is 96.485 kJ/mol). By contrast, most chemical oxidation reactions, such as burning coal, release at most a few eV. In a nuclear reactor, the energy is converted to heat as the particles and gamma rays collide with the atoms that make up the reactor and its working fluid, usually water or occasionally heavy water.

Fusion power, on the other hand, is generated by nuclear fusion reactions where two light atomic nuclei fuse together to form a heavier nucleus and in doing so, release a large amount of energy. If two light nuclei fuse, they will generally form

a single nucleus with a slightly smaller mass than the sum of their original masses. The difference in mass is released as energy according to Albert Einstein's mass-energy equivalence formula $E = mc^2$. The dividing line between "light" and "heavy" is iron-56. Above this atomic mass, energy will generally be released by nuclear fission reactions. Most fusion reactions combine isotopes of hydrogen that are protium, deuterium, or tritium to form isotopes of helium ^3He or ^4He. Most fusion power plants involve using the fusion reactions to create heat, which is then used to operate a steam turbine, which drives generators to produce electricity. This is similar to most coal, oil, and gas-fired power production plants [3].

Nuclear fusion requires precisely controlled temperature, pressure, and magnetic field parameters to generate net energy. If the reactor were damaged, these parameters would be disrupted and the heat generation in the reactor would rapidly cease. In contrast, the fission products in a fission reactor continue to generate heat for several hours or even days after reactor shutdown, meaning that melting of fuel rods is possible even after the reactor has been stopped due to continued accumulation of heat.

6.9 Hydropower Plants

Hydropower is a process in which the force of flowing water is used to spin a turbine connected to a generator to produce electricity. Most hydroelectric power comes from the potential energy of dammed water driving a turbine and generator. The power extracted from the water depends on the volume and the amount of potential energy in water is proportional to the head, which is difference in height between the source and the water's outflow. A simple formula for approximating electric power production at a hydroelectric plant is:

$$\dot{W} = \dot{Q}\rho g \Delta z = \dot{m} g \Delta z \tag{6.13}$$

where $\dot{W}$ is the power, ρ is the density of water (~ 1000 kg/m^3), Δz is the height, Q is the volumetric flow rate, and g is the acceleration due to gravity. Annual electric energy production depends on the available water supply. In some installations the water flow rate can vary by a factor of 10:1 over the course of a year. Example 6.12 illustrates the analysis of hydroelectric power output.

Hydropower eliminates the use of fossil fuels and hence carbon dioxide emission. Hydroelectric plants also tend to have longer economic lives (50 years or longer) than fuel-fired power production. The sale of hydroelectricity may cover the construction costs after 5–8 years of full operation [15]. Operating labor cost is also usually low, as plants are automated. The hydroelectric capacity is either the actual annual energy production or by installed capacity. A hydroelectric plant rarely operates at its full capacity over a full year. The ratio of annual average power output to installed capacity is the *capacity factor* for a hydroelectric power plant. There are large, small, and micro hydropower plant operations, which are summarized below.

- *Large hydroelectric power stations* have outputs from over a few hundred megawatts to more than 10 GW. Many large hydroelectric projects supply public electricity networks. The construction of these large hydroelectric facilities and the changes it makes to the environment are monitored by specialized organizations, such as the International Hydropower Association (http://hydropower.org/).
- *Small hydroelectric power plants* have a capacity of up to 10 MW. Some are created to serve specific industrial plants, such as for aluminum electrolytic plants, for which substantial amount of electricity is needed.
- Micro hydroelectric power installations typically produce up to 100 KW of power. These installations can provide power to an isolated home or small community. Sometimes, micro hydro systems may complement photovoltaic solar energy systems, because water flow and available hydro power may be highest in the winter when solar energy is at a minimum.

Example 6.12 Hydroelectric power output

A hydroelectric plant operates by water falling from a 200 ft height. The turbine in the plant converts potential energy into electrical energy, which is lost by about 5% through the power transmission so that the available power is 95%. If the mass flow rate of the water is 396 lb/s, estimate the power output of the hydro plant.

Solution:

Equation: $\dot{W} = \frac{\dot{m} g \Delta z}{g_c}$

Data: Δz = 200 ft, water flow rate 396 lb/s; transmission loss = 5%

$$\dot{W} = \frac{(396\,\text{lb/s})(32.2\,\text{ft}^2/\text{s})(200\,\text{ft})}{32.2\,\text{ft lb/lb}_\text{f}\text{s}^2}\left(\frac{1.055\,\text{kW}}{778\,\text{lb}_\text{f}\text{ft/s}}\right) = 107.4\,\text{kW}$$

With the transmission loss the available power: 107.4 kW (1−0.05) = **102.0 kW.**

6.10 Wind Power Plants

The Earth is unevenly heated by the sun and the differential heating drives a global atmospheric convection system leading to the wind. *Wind power* is the conversion of wind energy into electricity by using wind turbines. A wind turbine is a device for converting the kinetic energy in wind into the mechanical energy of a rotating shaft. The generator is usually connected to the turbine shaft through gears which turn the generator at a different speed than the turbine shaft. Power electronic controls and converts the electricity into the correct frequency and voltage to feed into the power grid at 60 or 50 Hertz.

The power produced by a wind turbine is proportional to the kinetic energy of the wind captured by the wind turbine. The kinetic energy of the wind is equal to the product of the kinetic energy of air per unit mass and the mass flow rate of air through the blade span area:

Wind power = (efficiency) (kinetic energy) (mass flow rate of air)

$$\dot{W}_{\text{wind}} = \eta_{\text{wind}} \frac{v^2}{2} (\rho A v) = \eta_{\text{wind}} \frac{v^2}{2} \rho \frac{\pi D^2}{4} v \tag{6.14}$$

After rearrangement, we have

$$\dot{W}_{\text{wind}} = \eta_{\text{wind}} \rho \frac{\pi v^3 D^2}{8} = (\text{constant}) v^3 D^2 \tag{6.15}$$

$$\text{constant} = \frac{\eta_{\text{wind}} \rho \pi}{8} \tag{6.16}$$

where ρ is the density of air, v is the velocity of air, D is the diameter of the blades of the wind turbine, and η_{wind} is the efficiency of the wind turbine. Therefore, the power produced by the wind turbine is proportional to the cube of the wind velocity and the square of the blade span diameter. The strength of wind varies, and an average value for a given location does not alone indicate the amount of energy a wind turbine could produce there. To assess the frequency of wind speeds at a particular location, a probability distribution function is often fit to the observed data.

At the end of 2009, the worldwide capacity of wind-powered generators was 159.2 GW. Large-scale wind farms are connected to the electric power transmission network, while the smaller facilities are used to provide electricity to isolated locations. Wind energy, as an alternative to fossil fuels, is plentiful, renewable, widely distributed, clean, and produces no greenhouse gas emissions during operation. Wind power is non-dispatchable, and for economic operation, all of the available output must be taken when it is available. Problems of variability are addressed by grid energy storage, batteries, pumped-storage hydroelectricity, and energy demand management. Wind power has negligible fuel costs, projected useful life of the equipment in excess of twenty years, but a high capital cost. The estimated average cost per unit includes the cost of construction of the turbine and transmission facilities [1, 24].

In a wind farm, individual turbines are interconnected with a medium voltage (often 34.5 kV), power collection system, and communications network. At a substation, this medium-voltage electric current is increased in voltage with a transformer for connection to the high voltage electric power transmission system. Wind turbine generators need extensive modeling of the dynamic electromechanical characteristics to ensure stable behavior. The ratio between annual average power and installed capacity rating of a wind-power production is the *capacity factor*. Typical capacity factors for wind power change between 20 and 40%. Example 6.13 illustrates the windmill calculations.

Wind energy penetration refers to the fraction of energy produced by wind compared with the total available production capacity. There is no generally accepted maximum level of wind penetration. An interconnected electricity grid usually includes reserve production and transmission capacity to allow for equipment failures; this reserve capacity can also serve to regulate for the varying power production by wind plants. At present, a few grid systems have penetration of wind energy above 5%: Despite the power forecasting methods used, predictability of wind plant output remains low for short-term operation. Pumped-storage hydroelectricity or other forms of grid energy storage can store energy developed by high-wind periods and release it when needed.

Apart from the availability of wind itself, other factors include the availability of transmission lines, value of energy, cost of land acquisition, land use considerations, and environmental impact of construction and operations. *Wind power density* is a calculation of the effective power of the wind at a particular location. A map showing the distribution of wind power density is a first step in identifying possible locations for wind turbines.

Small-scale wind power has the capacity to produce up to 50 kW of electrical power. Isolated communities may use small-scale wind turbines to displace fossil fuel consumption. Example 6.13 discusses the windmill power production.

Example 6.13 Windmill power estimations

A farm of windmills supplies a power output of 1 MW for a community. Each windmill has blades 10 m in diameter. At the location of the windmills, the average velocity of the wind is 11 m/s and the average temperature is 20°C. Estimate the minimum number of windmills to be installed.

Solution: Air is ideal gas and the pressure is atmospheric.
Inlet: $v = 11$ m/s, $R = 8.314$ kPa m^3/kmol K, $T = 293$ K, $D = 10$ m,
$MW_{\text{air}} = 29$ kg/kmol
Power output $= 1$ MW

$$\text{Density of air } \rho = (MW)\frac{P}{RT} = \frac{(29\,\text{kg/kmol})101.3\,\text{kPa}}{(8.314\,\text{kPa m}^3/\text{kmol K})(293\,\text{K})} = 1.2\,\text{m}^3/\text{kg}$$

Air mass flow rate: $\dot{m} = \rho A v = \rho \pi \frac{D^2}{4} v = 1036.2\,\text{kg/s}$

Power from each windmill:

$$KE = \dot{m}\frac{v^2}{2} = 1036.2\,\text{kg/s}\frac{(11\,\text{m/s})^2}{2}\left(\frac{\text{kJ/kg}}{1000\,\text{m}^2/\text{s}^2}\right) = 62.7\,\text{kW}$$

The minimum number of windmills to be installed:
1000 kW/62.7 kW = **16 windmills**

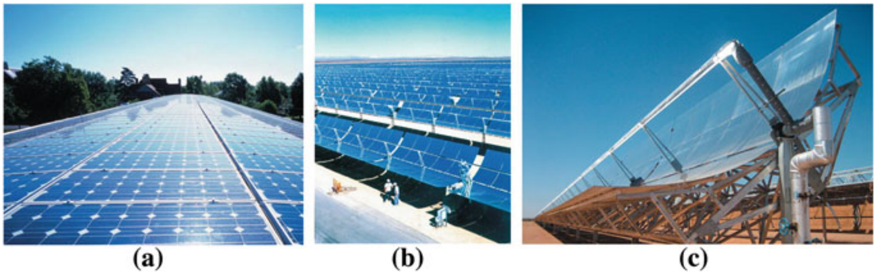
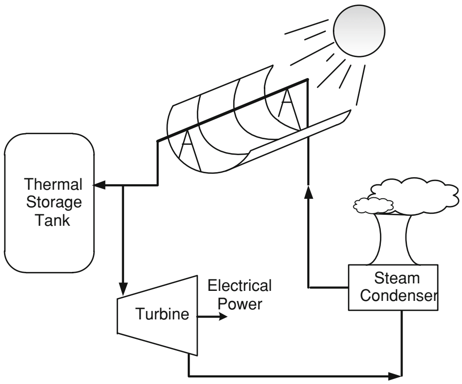


Fig. 6.15 **a** Photovoltaic system at Oberlin College's Adam Joseph Lewis Center for Environmental Studies **b** The 150-megawatt (MW) Kramer Junction plants shown here are part of a 354 MW series of SEGS (solar electric generating system) facilities, each using parabolic trough collectors to collect the sun's energy to generate steam to drive a conventional steam turbine. The plants have been operating in the California Mojave Desert for two decades. **c** Parabolic trough solar collectors at the recently dedicated 1-MW Saguaro power plant outside Tucson concentrate sunlight onto a receiver tube located along the trough's focal line. The solar energy heats the working fluid in the receiver tube, which vaporizes a secondary fluid to power a turbine [22]

Fig. 6.16 Concentrating solar power technologies offer utility-scale power production [12]



6.11 Solar Power Plants

Solar power is derived from the energy of sunlight. Average insolation changes from 150 to 300 W/m^2 or 3.5 to 7.0 kWh/m^2 day. There are two main types of technologies for converting solar energy to electricity: photovoltaic and solar–thermal electric (see Fig. 6.15 and Fig. 6.16).

- *Photovoltaic conversion* produces electricity directly from sunlight in a solar cell. There are many types of photovoltaic cells, such as thin film, mono-crystalline silicon, polycrystalline silicon, and amorphous cells, as well as multiple types of concentrating solar power. Photovoltaic power initially is

Fig. 6.17 **a** Stirling solar dish power production. **b** World's first commercial solar power tower located in Seville, Andalusia, Spain

used in small- and medium-sized applications, from the calculator powered by a single solar cell to off-grid homes powered by photovoltaic modules (see Fig. 6.15a)

- *Solar–thermal electric production* based on concentrating solar power systems use lenses or mirrors and tracking systems to focus a large area of sunlight into a small beam. The concentrated solar energy heat is used to produce steam to drive turbines and produce electricity. A parabolic trough consists of a linear parabolic reflector that concentrates light onto a receiver positioned along the reflector's focal line (see Figs. 6.15b, c, and 6.16). The receiver is a tube positioned right above the middle of the parabolic mirror and is filled with a working fluid. The reflector is made to follow the Sun during the daylight hours by tracking along a single axis [25].

A Stirling solar dish consists of a standalone parabolic reflector that concentrates light onto a receiver positioned at the reflector's focal point. The reflector tracks the sun along two axes and captures the sun's energy through a parabolic dish solar concentrator. The concentrated energy drives a Stirling engine, which spins a generator producing electricity [17]. Figure 6.17a shows a Stirling concentrating solar power system. The advantages of Stirling solar over photovoltaic cells are higher efficiency of converting sunlight into electricity and longer lifetime.

A solar power tower concentrates light on a central receiver atop a tower, which is mounted at the center of a large field (see Fig. 6.17b). Mirrors, called heliostats, track the sun throughout the day and reflect sunlight to the receiver. Early designs used water heated to steam by the sun's energy to drive turbines. New systems use liquid salt because of its thermal characteristics. The salt is usually a mixture of 60% sodium nitrate and 40% potassium nitrate. The mixture melts at 220°C/428°F. Cold salt is pumped from a holding tank through the receiver where the focused sunlight heats it to over 1000°F. The hot salt passes through a heat exchanger that makes steam to drive turbines. Power towers are more cost effective, offer higher

Table 6.1 Global hydrogen production

Source	(%)
Natural gas	48
Petroleum	30
Coal	18
Water	4

efficiency, and better energy storage capability among concentrated solar power technologies.

Solar installations in recent years have also begun to expand into residential areas, with governments offering incentive programs to make renewable (green) energy sources a more economically viable option [5].

6.12 Hydrogen Production

Hydrogen does not occur naturally and thus it must be generated from some other energy sources. Steam reforming of natural gas is the most common method of producing commercial bulk hydrogen. It is also the least expensive method. At high temperatures and in the presence of a metal-based catalyst (nickel), steam reacts with methane to yield carbon monoxide and hydrogen. These two reactions are reversible in nature.

$$CH_4 + H_2O \rightarrow CO + 3\ H_2 \quad (750{-}800^\circ C, \text{endothermic}) \tag{6.17}$$

Additional hydrogen can be recovered by a lower temperature gas-shift reaction

$$CO + H_2O \rightarrow CO_2 + H_2\ (\text{Low temperature shift at 190-210}^\circ C, \text{exothermic}) \tag{6.18}$$

Table 6.1 shows the global hydrogen production sources. Most hydrogen on earth is bonded to oxygen in water. Hydrogen is therefore an energy carrier like electricity, and not a primary energy source like natural gas. Hydrogen burns cleanly, producing little or no harmful emissions or CO_2. It has the highest energy content per unit of weight of any known fuel. When hydrogen is used in a fuel cell, its only waste is water.

To make hydrogen a renewable fuel, the production of it should use renewable energy, such as wind power or solar power. About half of the hydrogen produced is used for ammonia (NH_3) synthesis by the Haber process. The ammonia is used directly or indirectly as fertilizer. The other half of hydrogen is used to convert heavy petroleum sources into lighter fractions to use as fuels.

Hydrogen can also be produced by electrolysis of water, in which the water is split into hydrogen and oxygen

$$2H_2O \rightarrow 2H_2 + O_2 \tag{6.19}$$

The current best water-electrolysis processes have an efficiency of 50–80%, so that 1 kg of hydrogen requires 50–80 kWh of electricity. Using electricity produced by photovoltaic systems may offer the cleanest way to produce hydrogen. Photo electrochemical light harvesting systems may generate sufficient voltage to split water.

Hydrogen can also be produced via pyrolysis or gasification of biomass resources such as agricultural residues like peanut shells, consumer wastes including plastics and waste grease, or biomass specifically grown for energy uses. Biomass pyrolysis produces bio oil that contains a wide spectrum of valuable chemicals and fuels, including hydrogen. Highly concentrated sunlight can be used to generate the high temperatures needed to split methane into hydrogen and carbon in a solar-driven thermochemical process

$$CH_4 + \text{heat} \rightarrow C + 2H_2 \tag{6.20}$$

The produced hydrogen can be recycled to the Sabatier process.

6.13 Fuel Cells

A *fuel cell* oxidizes a fuel, such as hydrogen or methane, electrochemically to produce electric power. It consists of two electrodes separated by an electrolyte. The fuel and oxygen are continuously fed into the cell and the products of reaction are withdrawn continuously. The fuel makes intimate contact with the anode, fuel electrode. Oxygen, usually in air, makes intimate contact with the cathode, oxygen electrode. Half-cell reactions take place at each electrode. The sum of the half-cell reactions is the overall reaction. The type of electrolyte characterizes the type of fuel cell. Schematic fuel cell using hydrogen as fuel is illustrated in Fig. 6.18. When the electrolyte is acidic, the half-cell reactions occurring at the hydrogen electrode (anode) and at the oxygen electrode (cathode) are

$$H_2 \rightarrow 2H^+ + 2e^- \quad \text{(anode)} \tag{6.21}$$

$$\frac{1}{2}O_2 + 2e^- + 2H^+ \rightarrow H_2O(g) \quad \text{(cathode)} \tag{6.22}$$

The electrons with negative charge (e^-) are released at the anode. These electrons produce an electric current which is used by the reaction occurring at the cathode. The electric current is carried out by an external circuit. The cation H^+ migrates from anode to cathode through the electrolyte. The sum of the half-cell reactions is the overall reaction taking place at the fuel cell

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O(g) \tag{6.23}$$

A thin solid polymer known as *proton exchange membrane* serves as an acid electrolyte in the hydrogen/oxygen fuel cell. Each side of the membrane is bonded

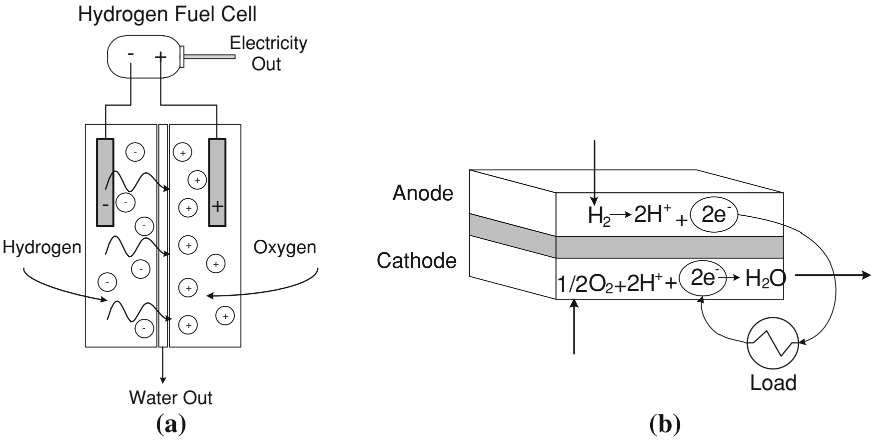


Fig. 6.18 **a** Schematic of a hydrogen fuel cell. The waste product is water. Source, **b** half-cell reactions for a hydrogen/oxygen fuel cell with acidic electrolyte

to a porous carbon electrode impregnated with platinum which serves as a catalyst. The porous electrode provides a very large interface area for the reaction and facilitates the diffusion of hydrogen and oxygen into the cell and the water vapor out of the cell. Cells can be connected in series to make a compact unit with a required level of energy output and operate at a temperature near 60°C.

For each mole of hydrogen consumed, 2 mol of electrons pass to the external circuit. Therefore, the electrical energy (work) is the product of the charge transferred and the voltage V of the cell

$$W_e = -2FV = \Delta G \tag{6.24}$$

where F is the Faraday's constant ($F = 96485$ coulomb/mol) and ΔG is the Gibbs energy. The electric work of reversible and isothermal fuel cell is

$$W_e = \Delta H - q = \Delta G \tag{6.25}$$

Consider a hydrogen/oxygen fuel cell operating at 20°C and 1 bar with pure hydrogen and oxygen as reactants and water vapor as product. The overall reaction is the standard formation reaction for water and the from Appendix C Table C1, we have

$$\Delta H = \Delta H^o_{f,\mathrm{H_2O}} = -241,818\,\mathrm{J/mol} \text{ and } \quad \Delta G = \Delta G^o_{f,\mathrm{H_2O}} = -228,572\,\mathrm{J/mol}$$

Therefore, for the hydrogen/oxygen fuel cell the electric work and the voltage are

$$\mathrm{W_e} = -228,572\,\mathrm{J/mol} \text{ and } \quad V = \frac{-\Delta G}{2F} = 1.184\,\mathrm{V}$$

Using the air instead of pure oxygen in a reversible and isothermal fuel cell, we have

$$W_e = -226{,}638\,\text{J/mol and} \quad V = 1.174\,\text{volts(hydrogen/air fuel cell)}$$

In practice, operating voltage of hydrogen/oxygen fuel cell is around 0.6–0.7 volts, because of internal irreversibilities which reduce the electric work produced and increase the heat transfer to the surroundings.

Fuel cells are very efficient, but expensive to build. Small fuel cells can power electric cars. Large fuel cells can provide electricity in remote places with no power lines. Because of the high cost to build fuel cells, large hydrogen power plants may not be built in the near future. However, fuel cells are being used in some places as a source of emergency power, from hospitals to wilderness locations. Portable fuel cells are being manufactured to provide longer power for laptop computers, cell phones, and military applications [23, 34].

6.13.1 Direct Methanol Fuel Cells

Direct methanol fuel cells are a subcategory of proton exchange fuel cells in which methanol is used as the fuel. Methanol is toxic, flammable, and a liquid from −97.0 to 64.7°C at atmospheric pressure. Methanol is fed as a weak solution (usually around 1 M, i.e. about 3% in mass). At the anode, methanol and water are adsorbed on a catalyst usually made of platinum and ruthenium particles, and lose protons until carbon dioxide is formed. Direct methanol fuel cells use a methanol solution to carry the reactant into the cell; common operating temperatures are in the range 50–120°C. Water is consumed at the anode and is produced at the cathode. Protons (H^+) are transported across the proton exchange membrane often made from Nafion to the cathode where they react with oxygen to produce water. Electrons are transported through an external circuit from anode to cathode, providing power to connected devices. The half-reactions taking place at the anode and cathode, and the overall reactions of the cell are

$$CH_3OH + H_2O \rightarrow CO_2 + 6H^+ + 6e^- \quad \text{(Anode)} \tag{6.26}$$

$$3/2\ O_2 + 6H^+ + 6e^- \rightarrow 3H_2O \quad \text{(Cathode)} \tag{6.27}$$

$$CH_3OH + 3/2\ O_2 \rightarrow CO_2 + 2H_2O + \text{electrical energy (Overall Reaction)} \tag{6.28}$$

The only waste products with these types of fuel cells are carbon dioxide and water. Currently, platinum is used as the catalyst for both half-reactions. Efficiency is presently quite low for these cells, so they are targeted especially to portable application, where energy and power density are more important than efficiency. These cells need improvements for the loss of methanol and the management of carbon dioxide created at the anode.

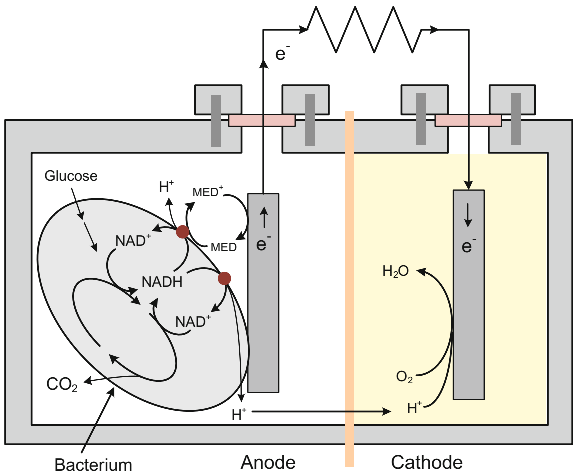


Fig. 6.19 A general layout of a microbial fuel cell in which in the anodic compartment the bacteria can bring about oxidative conversions while in the cathodic compartment chemical and microbial reductive processes can occur [30]

6.13.2 Microbial Fuel Cell

A *microbial fuel cell* converts chemical energy, available in a bio substrate, directly into electricity. To achieve this, bacteria are used as a catalyst to convert a variety of organic compounds into CO_2, water, and energy. The microorganisms use the produced energy to grow and to maintain their metabolism. A microbial fuel cell can harvest a part of this microbial energy in the form of electricity. A microbial fuel cell consists of an anode, a cathode, a proton exchange membrane, and an electrical circuit as seen in Fig. 6.19. The bacteria live in the anode and convert a bio substrate such as glucose, acetate but also waste water into CO_2, protons, and electrons

$$C_{12}H_{22}O_{11} + 13H_2O \rightarrow 12CO_2 + 48H^+ + 48e^- \tag{6.29}$$

Due to the ability of bacteria to transfer electrons to an insoluble electron acceptor, microbial fuel cell collects the electrons originating from the microbial metabolism. The electrons then flow through an electrical circuit to the cathode. The potential difference (Volt) between the anode and the cathode, together with the flow of electrons (Ampere) results in the generation of electrical power. The protons flow through the proton exchange membrane to the cathode. At the cathode the electrons, oxygen, and protons combine to form only water. The two electrodes are at different potentials (about 0.5 V). Microbial fuel cells use inorganic mediators to tap into the electron transport chain of cells and channel electrons produced. Some possible mediators include natural red, methylene blue, or thionine. The mediator exits the cell laden with electrons that it shuttles to an electrode where it deposits them. This electrode becomes the anode negatively

charged electrode. After releasing the electrons, the mediator returns to its original oxidized state ready to repeat the process. Therefore, the microbial activity is strongly dependent on the redox potential of the anode [30].

6.14 Biomass and Bioenergy Production

Biomass is material derived from recently living organisms, which includes plants, animals, and their by-products. It is a renewable energy source based on the carbon cycle. Some agricultural products grown for biofuel production include corn, soybeans, willow switchgrass, rapeseed, wheat, sugar beet, palm oil, miscanthus, sorghum, cassava, and jatropha [2]. Biodegradable outputs from the industry, agriculture, forestry, and households can be used for biofuel production, using for example: (i) anaerobic digestion to produce biogas, (ii) gasification to produce syngas (H_2 + CO), or (iii) by direct combustion. These materials can be burned directly in steam-electric power plants, or converted to gas that can be burned in steam generators, gas turbines, or internal combustion engine generators. Biomass accounts for about 1% of the electricity generated in the United States. The use of biomass can therefore contribute to waste management as well as fuel.

Bioenergy is renewable energy derived from biological sources, to be used for heat, electricity, or vehicle fuel. Biofuel derived from plant materials is among the most rapidly growing renewable energy technologies. In the United States, corn-based ethanol is currently the largest source of biofuel as a gasoline substitute or additive. As bioenergy is the energy extracted from the biomass, the biomass is the fuel and the bioenergy is the energy contained in the fuel [18].

Biomass can be fermented directly to produce hydrogen, ethanol, and high-value chemicals. Certain photosynthetic microbes produce hydrogen from water in their metabolic activities using light energy. Photo biological technology holds great promise, but because oxygen is produced along with the hydrogen, the technology must overcome the limitation of oxygen sensitivity of the hydrogen-evolving enzyme systems. A new system is also being developed that uses a metabolic switch (sulfur deprivation) to cycle algal cells between a photosynthetic growth phase and a hydrogen production phase.

The production processes of sugar and ethanol in Brazil takes full advantage of the energy stored in sugarcane. Part of the bagasse is currently burned at the mill to provide heat for distillation and electricity to run the machinery. This allows ethanol plants to be energetically self-sufficient and even sell surplus electricity to utilities. Estimates of potential power generation from bagasse range from 1,000 to 9,000 MW, depending on technology.

6.14.1 Bioethanol Production

Ethanol is a clear, colorless alcohol fuel made from the sugars found in grains, such as corn, sorghum, and barley, sugar cane, and sugar beets. Therefore, ethanol is a renewable fuel. The most common processes to produce ethanol today use yeast to ferment the sugars (glucose) and starch. Sugar cane and sugar beets are also common sources used to produce ethanol. Fermentation is a natural microbiological process where sugars are converted to alcohol and carbon dioxide by yeast (*Saccharomyces cerevisiae*—a type of fungi) in about 24–36 h. The overall reaction within the yeast may be represented by

$$\begin{gathered} C_6H_{12}O_6 \rightarrow 2(CH_3CH_2OH) + 2CO_2 \\ \text{Sugar} \rightarrow \text{Alcohol} + \text{Carbon dioxide gas} \end{gathered} \tag{6.30}$$

The resulting solution is distilled to get pure ethanol. For each pound of simple sugars, yeast can produce approximately 1/2 pound (0.15 gal) of ethanol and an equivalent amount of carbon dioxide. Corn consists of 72% starch, which is broken down into simple sugar by adding an enzyme (glucoamylase) so it can be fermented with yeast. By-products include high fructose corn syrup, food additives such as citric acid, corn oil (cooking oil), and livestock feed.

With advanced technology, cellulosic biomass, such as trees and grasses, can also be used as feedstock for ethanol production by using acids or enzymes to create sugars that can be fermented. Cellulosic ethanol involves a more complicated production process than conventional ethanol made from fermentation of starches or sugars. However, this process can reduce concerns that increasing ethanol production will reduce food supply. Cellulosic biomass requires less energy, fertilizers, and water than grains. Cellulosic biomass can also be grown on lands that are not suitable for growing food. Many grasses can produce two harvests a year for many years without a need for annual replanting [14, 35].

6.14.2 Biodiesel and Green Diesel Production

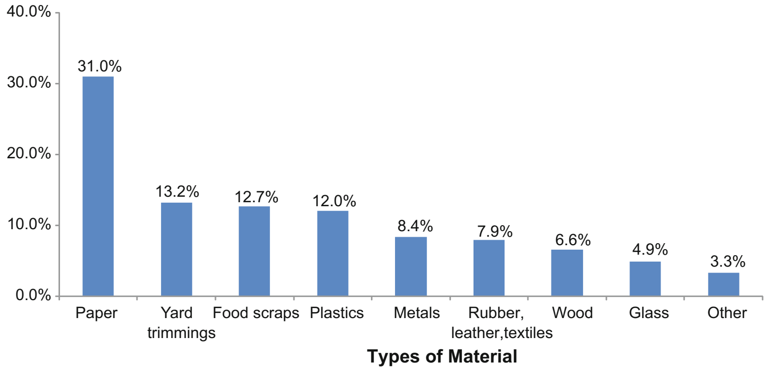
Biodiesel production involves transesterification of feedstock of vegetable oils or animal fats catalytically with a short-chain aliphatic alcohol typically methanol. One hundred pounds of fat or oil such as soybean oil are reacted with 10 pounds of a short-chain alcohol in the presence of a catalyst to produce 10 pounds of glycerin and 100 pounds of biodiesel. R', R'', and R''' indicate the fatty acid chains

associated with the oil or fat which are largely palmitic, stearic, oleic, and linoleic acids for naturally occurring oils and fats.

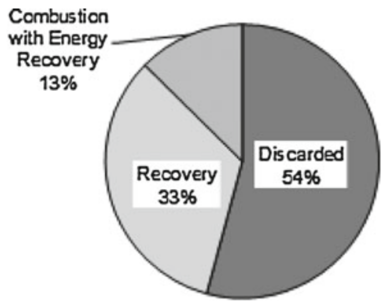
$$\begin{array}{cccccccc}
CH_2OCOR''' & & & & CH_2OH & & R'''COOR & \\
| & & & \text{Catalyst} & | & & & \\
CH_2OCOR'' & + & 3\ ROH & \text{------>} & CH_2OH & + & R''COOR & \\
| & & & & | & & & \\
CH_2OCOR' & & & & CH_2OH & & R'COOR & \quad (6.31) \\
 & & & & & & & \\
\text{100 pounds} & & \text{10 pounds} & & \text{10 pounds} & & \text{100 pounds} & \\
\text{Oil or Fat} & & \text{Alcohol (3)} & & \text{Glycerin} & & \text{Biodiesel (3)} &
\end{array}$$

The base-catalyzed reaction occurs at low temperature and pressure, yields high conversion (98%) with minimal side reactions and reaction time. Animal and plant fats and oils are typically made of triglycerides which are esters containing three free fatty acids and the glycerol. Water and other non-oil materials should be removed from the feedstock. Water causes the triglycerides to hydrolyze, giving salts of fatty acids (soaps). Sufficient alcohol is added to make up an excess of usually six parts alcohol to one part triglyceride for the reaction to complete. A titration estimates how much alkaline is needed to completely neutralize any free fatty acids present, thus ensuring a complete transesterification. The reaction take place around 55°C (131°F). Reaction time varies from 1 to 8 h. Products of the reaction include not only biodiesel, but also, glycerin, excess alcohol, and some water. All of these by-products must be removed. Residual methanol is typically removed through distillation and recycled to the reactor [8].

Green diesel is produced by removing the oxygen by catalytic reaction with hydrogen from renewable feedstock containing triglycerides and fatty acids, producing a paraffin-rich product, water, and carbon oxides [19]. Triglycerides and fatty free acids both contain long, linear aliphatic hydrocarbon chains, which are partially unsaturated and have a carbon number range similar to the molecules found in petroleum diesel fuels. Therefore, green diesel has a heating value equal to conventional diesel and is fully compatible for blending with the standard mix of petroleum-derived diesel fuels. Biodiesel has around 11% oxygen, whereas petroleum-based diesel and green diesel have no oxygen. Petroleum diesel has around 10 ppm sulfur and biodiesel and green diesel have less than 1 ppm sulfur. Fossil fuel consumption over the life cycle is expected to be reduced by 84–90% for green diesel produced from soybean oil or palm oil, respectively, when hydrogen is produced from renewable resources. Feedstocks rich in saturated fats, such as palm and tallow oil, require less hydrogen than feedstocks higher in olefin content, such as soybean or rapeseed oil [19]. The yield of green diesel depends on both feedstock type and the level of hydroisomerization required to achieve product cloud point specification.



(a)



(b)

Fig. 6.20 **a** Generation of municipal solid waste. **b** Management of municipal solid waste [13]

6.14.3 Energy from Solid Waste

Garbage, often called municipal solid waste, is the source of about 12% of the total biomass energy consumed in the United States. Municipal solid waste contains biomass like paper, cardboard, food scraps, grass clippings, leaves, wood, and leather products, and other non-biomass combustible materials, mainly plastics and other synthetic materials made from petroleum (see Fig. 6.20).

Recycling and composting programs may reduce the share of biomass in municipal solid waste that is land filled or burned. Solid waste can be burned in special waste-to-energy plants, which produce heat to make steam to heat buildings or to produce electricity. Such plants help reduce the amount of solid waste to be buried in landfills. There are also solid waste incinerators that simply burn the solid waste without electricity production.

6.15 Other Energy Production Opportunities

There are other energy production systems and processes either under development or operation with limited scale [29]. Some of these energy production opportunities are:

- *Solid-state generation* (without moving parts) is of particular interest in portable applications. This area is largely dominated by thermoelectric devices, though thermionic and thermophotovoltaic systems have been developed as well.
- *Piezoelectric devices* are used for power generation from mechanical strain, particularly in power harvesting.
- *Betavoltaics* are another type of solid-state power generator which produces electricity from radioactive decay.
- *Fluid-based magnetohydrodynamic* power generation has been studied as a method for extracting electrical power from nuclear reactors and also from more conventional fuel combustion systems.
- *Osmotic power* finally is another possibility at places where salt and sweet water merges in rivers and seas.
- Electromagnetic Energy Harvesting.
- Harvesting Circuits.
- Thermoelectrics.
- Microbatteries.

6.16 Levelized Energy Cost

Levelized energy cost is the price at which electricity must be produced from a specific source to break even. It is an economic assessment tool in calculating the costs of generation from different sources. The costs include initial investment, operations and maintenance, cost of fuel, and cost of capital. It can be defined in a single formula as [12]

$$LEC = \frac{\sum_{i}^{n} \frac{I_i + M_i + F_i}{(1+r)^i}}{\sum_{i}^{n} \frac{E_i}{(1+r)^i}} \tag{6.32}$$

- LEC = Average lifetime levelised electricity generation cost
- I = Investment expenditures
- M = Operations and maintenance expenditures
- F = Fuel expenditures
- E = Electricity production

Table 6.2 Estimated levelized cost of new generation resources plants entering service in 2016

Plant type	Capacity factor (%)	U.S. average Levelized costs[a] (2009) ($/MW h)			
		Capital cost	Operating and maintenance	Transmission investment	Average total cost
Conventional coal	85	65.3	28.1	1.2	94.8
Advanced coal	85	74.6	33.6	1.2	109.4
Natural gas-fired combined cycle	87	17.5	47.5	1.2	66.1
Advanced combined cycle	87	17.9	44.0	1.2	63.1
Conventional combustion turbine	30	45.8	75.1	3.5	124.5
Advanced combustion turbine	30	31.6	68.4	3.5	103.5
Advanced nuclear	90	90.1	22.8	1.0	113.9
Wind	34	83.9	9.6	3.5	97.0
Wind—Offshore	34	209.3	28.1	5.9	243.2
Solar PV[1]	25	194.6	12.1	4.0	210.7
Solar thermal	18	259.4	46.6	5.8	311.8
Geothermal	92	79.3	21.4	1.0	101.7
Biomass	83	55.3	56.0	1.3	112.5
Hydro	52	74.5	10.1	1.9	86.4

[a] Costs are expressed in terms of net AC power available to the grid for the installed capacity
Source Energy Information Administration [12]

- r = Interest rate
- n = Useful life of operation

Typically levelized energy costs are calculated over 20- to 40-year lifetimes, and are given in the units of currency per kilowatt-hour, for example $/kWh or $/MW h. When comparing levelized energy costs for alternative systems typically only the costs of connecting the generating source into the transmission system is included. Table 6.2 lists the estimated cost of electricity by source for plants entering service in 2016 from a December 16, 2010 report of the U.S. Department of Energy (DOE). Total system levelized cost gives the dollar cost per MW h that must be charged over time in order to pay for the total cost. These calculations take into account the level of carbon dioxide produced by coal plants. Levelized cost represents the present value of the total cost of building and operating a generating plant over an assumed useful life of operation by taking into account capital cost, fuel cost, operation and maintenance costs, financing costs, and an assumed utilization rate for each plant type.

- Capital costs tend to be low for fossil fuel power stations; high for wind turbines, solar photovoltaic, and nuclear. The capital costs are usually high for waste to energy, wave and tidal, and solar thermal plants.

- Operating and maintenance costs tend to be high for nuclear, coal, and waste-to-energy (ash disposal, emissions clean up, operating steam generators) and low for wind turbines, solar photovoltaic, renewables, and oil and gas-fired units.
- Fuel costs are high for fossil fuel and biomass sources, very low for nuclear and renewables.
- Revenue from the sales of heat can balance operating costs, and reduce the net costs in the case of cogeneration that is combined heat and power generation and district heating schemes.
- The costs of waste, waste treatment, and insurance costs are not included.

To evaluate the total cost of production of electricity, the costs are converted to a net present value using the time value of money. These costs are all brought together using cumulative discounted cash flows over the useful life of operation. Table 6.2 shows the levelized cost of new generation resources in the annual energy outlook 2011 [12].

6.17 Thermodynamic Cost

Thermodynamic cost takes into account irreversibilities that reduces the available energy in a process. Thermoeconomics assigns costs to exergy-related variables by using the *exergy cost theory* and *exergy cost balances* by using: (a) cost accounting methods and optimization methods, such as exergy cost theory for a rational price assessment, and (b) optimization by minimizing the overall cost under a proper set of financial, environmental, and technical constraints, to identify the optimum design and operating conditions. Cost accounting methods use average costs as a basis for a rational price assessment, while optimization methods employ marginal costs in order to minimize the costs of the products of a system or a component. *Extended exergy* accounts for the environmental impact in a more systematic way by estimating the resource-based value of a commodity. Consider a separation process with outputs containing hot streams with various chemicals having conditions considerably different from environmental temperatures and concentrations. To achieve zero environmental impact, these streams must be brought to both thermal and chemical equilibrium with the surroundings [9, 20, 26]. Example 6.14 illustrates the cost calculations in power production.

6.18 Ecological Cost

Ecological cost analysis may minimize the depletion of nonrenewable natural resources. Determining the extraction of raw materials and fossil fuels from natural resources is not sufficient in fully understanding the ecological impact of

production processes. The production, conversion, and utilization of energy may lead to environmental problems, such as air and water pollution, impact on the use of land and rivers, thermal pollution due to mismanagement of waste heat, and global climate change. The influence of waste products discharged into the environment should also be considered. The waste products may be harmful to agriculture, plant life, human health, and industrial activity.

6.18.1 Ecological Planning

Ecological planning for sustainable development should take into account the uncontrollable waste exergy emission in the environment. There are environmental impacts associated with the production and transmission of electricity. Emissions that result from the combustion of the fossil fuels include carbon dioxide (CO_2), carbon monoxide (CO), sulfur dioxide (SO_2), nitrogen oxides (NO_x), particulate matter, and heavy metals such as mercury. Nearly all combustion byproducts may have negative impacts on the environment and human health [11, 16, 22]:

- CO_2 is a greenhouse gas and a source of global warming. Power plants that burn fossil fuels and materials made from fossil fuels and some geothermal power plants are the sources of about 40% of the total U.S. carbon dioxide emissions.
- SO_2 causes acid rain, which is harmful to plants and animals that live in water, and it worsens or causes respiratory illnesses and heart diseases, particularly in children and the elderly. SO_2 emissions are controlled by wet and dry scrubbers, which involve mixing lime in the fuel (coal) or spraying a lime solution into the combustion gases. Fluidized bed combustion can also be used to control SO_2.
- NO_x contributes to ground level ozone, which irritates and damages the lungs. NO_x emissions can be controlled by several different techniques and technologies, such as low NO_x burners during the combustion phase or selective catalytic and non-catalytic converters during the post combustion phase.
- Particulate matter results in hazy conditions in cites and scenic areas, and, along with ozone, contributes to asthma and chronic bronchitis, especially in children and the elderly. Very small or "fine particulate matter" is also thought to cause emphysema and lung cancer. Heavy metals such as mercury can be hazardous to human and animal health. Particulate matter emissions are controlled with devices that clean the combustion gases that exit the power plant, such as "Baghouses" use large filters, electrostatic precipitators use charged plates, and wet scrubbers use a liquid solution.

6.18.2 Coal-Fired Power Plants

Coal-fired power plants are required to meet standards that limit the amounts of some of the substances that they release into the air:

- Coal-fired plants can use coal that is low in sulfur content. Coal can also be pretreated and processed to reduce the types and amounts of undesirable compounds in combustion gases.
- The coarse solid residue that results from burning solid fuels is called ash. The largest particles collect at the bottom of the boiler and are removed and quenched with water. Smaller and lighter particulates are called fly ash and are collected in air emission control devices, and are usually mixed with the bottom ash.
- Power transmission and distribution lines, using towers, carry electricity from power plants to customers. The towers and lines impact the visual landscape and disturb trees near the wires, native plant populations, and wildlife. Power lines under the ground are more expensive and may result in a greater disturbance of the landscape than overhead lines.

6.18.3 Nuclear Power Plants

Nuclear power plants are not a source of greenhouse gases or other emissions, but they do produce two kinds of radioactive wastes [3]:

- *Low-level radioactive waste*—This includes items that have become contaminated with radioactive material, such as clothing, wiping rags, mops, filters, reactor water treatment residues, and equipment and tools. Low-level waste is stored at nuclear power plants until the radioactivity in the waste decays to a level where it is allowed to be disposed of as ordinary trash or it is sent to a low-level waste disposal site.
- *Spent* (*used*) *nuclear fuel*—The spent fuel assemblies are highly radioactive and must initially be stored in specially designed pools resembling large swimming pools (water cools the fuel and acts as a radiation shield) or in specially designed dry storage containers. An increasing number of reactor operators now store their older spent fuel in dry storage facilities using special outdoor concrete or steel containers with air cooling.

Problems

6.1. In a steam-power plant, steam at 200 psia and 600°F enters a turbine and exits at 5 psia and 200°F. The steam enters the turbine through a 2.5-inch-diamateter pipe with a velocity of 11 ft/s and exits through a 9-inch-diamater pipe. Estimate the power produced by the turbine.

6.2. A turbine operates at adiabatic and steady-state conditions. At the inlet a steam at 600°C and 1100 kPa enters the turbine. The steam flow rate is 3 kg/s. The inlet tube diameter is 10 cm. After expanding in the turbine, the steam exits through a pipe of diameter 25 cm. At the exit the steam is at 300°C and 110 kPa. Estimate the work produced by the turbine.

6.3. A turbine operates at adiabatic and steady-state conditions. At the inlet a steam at 550°C and 1500 kPa enters the turbine. The steam flow rate is 4 kg/s. The inlet tube diameter is 12 cm. After expanding in the turbine, the steam exits through a pipe of diameter 28 cm. At the exit the steam is saturated at 110 kPa (at 102.3°C). Estimate the work produced by the turbine.

6.4. A turbine operates at adiabatic and steady-state conditions. At the inlet a steam at 600°C and 4000 kPa enters the turbine. The steam flow rate is 10 kg/s. The inlet tube diameter is 10 cm. After expanding in the turbine, the steam exits through a pipe of diameter 30 cm. At the exit the steam is at 150 kPa and 120°C. Estimate the work produced by the turbine.

6.5. A turbine operates at adiabatic and steady-state conditions. At the inlet a steam at 600°C and 8000 kPa enters the turbine. The steam flow rate is 15 kg/s. The inlet tube diameter is 9 cm. After expanding in the turbine, the steam exits through a pipe of diameter 35 cm. At the exit the steam is saturated at 100 kPa (99.63°C). Estimate the work produced by the turbine.

6.6. A superheated steam at 4100 kPa and 300°C expands adiabatically in a steam turbine and exits at 15 kPa with a quality of $x = 0.87$. Velocity of the steam at the inlet is 50 m/s and at the exit 160 m/s. Elevation at the inlet is 10 m and at the exit 6 m. Estimate the power produced for the steam flow rate of 1 kg/s.

6.7. A turbine serves as an energy source for a small electrical generator. The turbine operates at adiabatic and steady-state conditions. At the inlet a steam at 600°C and 1100 kPa enters the turbine. The steam flow rate is 3 kg/s. At the exit the steam is at 300°C and 110 kPa. Estimate the work produced by the turbine.

6.8. A steam at 8000 kPa and 400°C expands in a turbine. At the exit the steam is at 20 kpa with a quality of 0.9. Estimate the power output if the steam flow rate is 11.5 kg/s.

6.9. A steam at 8400 kPa and 400°C expands in a turbine. At the exit the steam is at 15 kpa with a quality of 0.92. Estimate the power output if the steam flow rate is 11.5 kg/s.

6.10. A steam expands in a turbine. The steam enters the turbine at 9000 kPa and 450°C and exits at 10 kPa with a quality of 0.95. If the turbine produces a power of 6.5 MW estimate the steam flow rate.

6.11. A hot exhaust gas is heating a boiler to produce superheated steam at 100 psia and 400°F. In the meantime, the exhaust gas is cooled from 2500 to 350°F. Saturated liquid water (stream 1) at 14.7 psia enters the boiler with a flow rate of 200 lb/h. Superheated steam (stream 2) is used in a turbine, and discharged as saturated steam (stream 3) at 14.7 psia. Determine the molar flow rate of the exhaust gas needed and the maximum work produced. Assume that the surroundings are at 70°F, and the heat capacity of the flue gas is $C_p = 7.606 + 0.0006077T$, where T is in Rankine and C_p is in Btu/(lbmol R).

6.12. A steam expands in a turbine. The steam enters the turbine at 1000 psia and 800°F and exits as a saturated vapor at 5 psia. The turbine produces a power of 5 MW. If the steam flow rate is 20 lb/s, estimate the heat loss from the turbine.

6.13. A turbine serves as an energy source for a small electrical generator. The turbine operates at adiabatic and steady-state conditions. At the inlet a steam at 550°C and 1500 kPa enters the turbine. The steam flow rate is 4 kg/s. At the exit the steam is saturated at 110 kPa (at 102.3°C). Estimate the work produced by the turbine.

6.14. A turbine serves as an energy source for a small electrical generator. The turbine operates at adiabatic and steady-state conditions. At the inlet a steam at 600°C and 4000 kPa enters the turbine. The steam flow rate is 10 kg/s. At the exit the steam is at 150 kPa and 120°C. Estimate the work produced by the turbine.

6.15. A turbine serves as an energy source for a small electrical generator. The turbine operates at adiabatic and steady-state conditions. At the inlet a steam at 600°C and 8000 kPa enters the turbine. The steam flow rate is 15 kg/s. At the exit the steam is saturated at 100 kPa (99.63°C). Estimate the work produced by the turbine.

6.16. Steam at 8200 kPa and 823.15 K (state 1) is being expanded to 30 kPa in a continuous operation. Determine the final temperature (state 2), entropy produced, and work produced per kg of steam for an isothermal expansion through a turbine.

6.17. Steam enters an adiabatic turbine at 5000 kPa and 450°C and leaves as a saturated vapor at 140 kPa. Determine the work output per kg of steam flowing through the turbine if the process is reversible and changes in kinetic and potential energies are negligible.

6.18. Steam at 8200 kPa and 823.15 K (state 1) is being expanded to 30 kPa in a continuous operation. Determine the final temperature (state 2), entropy produced, and work produced per kg of steam for an adiabatic expansion through a turbine.

6.19. A steady flow adiabatic turbine receives steam at 650 K and 8200 kPa, and discharges it at 373.15 K and 101.32 kPa. If the flow rate of the steam is 12 kg/s determine (a) The maximum work and (b) The work loss if the surroundings are at 298.15 K.

6.20. A turbine discharges steam from 6 MPa and 400°C to saturated vapor at 360.15 K while producing 480 kJ/kg of shaft work. The temperature of surroundings is 300 K. Determine the maximum possible production of power in kW.

6.21. A Carnot cycle uses water as the working fluid in a steady-flow process. Heat is transferred from a source at 400°C and water changes from saturated liquid to saturated vapor. The saturated steam expands in a turbine at 10 kPa, and a heat of 1150 kJ/kg is transferred in a condenser at 10 kPa. Estimate the net power output of the cycle for a flow rate of 10 kg/s of the working fluid.

6.22. A Carnot cycle uses water as the working fluid in a steady-flow process. Heat is transferred from a source at 400°C and water changes from saturated liquid to saturated vapor. The saturated steam expands in a turbine at 30 kPa, and a heat of 1150 kJ/kg is transferred in a condenser at 30 kPa. Estimate the net power output of the cycle for a flow rate of 14.5 kg/s of the working fluid.

6.23. A steam power production plant uses steams at 8200 kPa and 823.15 K. The turbine discharges the steam at 30 kPa. The turbine and pump operate reversibly and adiabatically. Determine the work produced for every kg steam produced in the boiler.

6.24. A steam power plant operates on a simple ideal Rankine cycle shown below. The turbine receives steam at 698.15 K and 4400 kPa, while the discharged steam is at 15 kPa. The mass flow rate of steam is 12.0 kg/s. Determine the net work output.

6.25. A reheat Rankine cycle is used in a steam power plant. Steam enters the high-pressure turbine at 9000 kPa and 823.15 K and leaves at 4350 kPa. The steam is reheated at constant pressure to 823.15 K. The steam enters the low-pressure turbine at 4350 kPa and 823.15 K. The discharged steam from the low-pressure turbine is at 10 kPa. The steam flow rate is 24.6 kg/s. Determine the net power output.

6.26. A reheat Rankine cycle is used in a steam power plant. Steam enters the high-pressure turbine at 10000 kPa and 823.15 K and leaves at 4350 kPa. The steam is reheated at constant pressure to 823.15 K. The steam enters the low-pressure turbine at 4350 kPa and 823.15 K. The discharged steam from the low-pressure turbine is at 15 kPa. The steam flow rate is 38.2 kg/s. Determine the net power output.

6.27. A simple ideal reheat Rankine cycle is used in a steam power plant shown below. Steam enters the turbine at 9200 kPa and 823.15 K and leaves at 4350 kPa and 698.15 K. The steam is reheated at constant pressure to 823.15 K. The discharged steam from the low-pressure turbine is at 15 kPa. The net power output of the turbine is 75 MW. Determine the mass flow rate of steam.

6.28. A steam power plant is using an actual regenerative Rankine cycle. Steam enters the high-pressure turbine at 11000 kPa and 773.15 K, and the condenser operates at 10 kPa. The steam is extracted from the turbine at

475 kPa to heat the water in an open heater. The water is a saturated liquid after passing through the water heater. The steam flow rate is 65 kg/s. Determine the work output.

6.29. A steam power plant is using an actual regenerative Rankine cycle. Steam enters the high-pressure turbine at 10000 kPa and 773.15 K, and the condenser operates at 30 kPa. The steam is extracted from the turbine at 475 kPa to heat the water in an open heater. The water is a saturated liquid after passing through the water heater. The steam flow rate is 45.6 kg/s. Determine the work output.

6.30. A steam power plant is using an ideal regenerative Rankine cycle shown below. Steam enters the high-pressure turbine at 8400 kPa and 773.15 K, and the condenser operates at 10 kPa. The steam is extracted from the turbine at 400 kPa to heat the feed water in an open heater. The water is a saturated liquid after passing through the feed water heater. Determine the net power output of the cycle.

6.31. A steam power plant is using an actual reheat regenerative Rankine cycle. Steam enters the high-pressure turbine at 11000 kPa and 773.15 K, and the condenser operates at 10 kPa. The steam is extracted from the turbine at 2000 kPa to heat the water in an open heater. The steam is extracted at 475 kPa for process heat. The water is a saturated liquid after passing through the water heater. Determine the work output for a flow rate of steam of 66.0 kg/s.

6.32. A steam power plant is using an ideal reheat regenerative Rankine cycle. Steam enters the high-pressure turbine at 9400 kPa and 773.15 K and leaves at 850 kPa. The condenser operates at 15 kPa. Part of the steam is extracted from the turbine at 850 kPa to heat the water in an open heater, where the steam and liquid water from the condenser mix and direct contact heat transfer takes place. The rest of the steam is reheated to 723.15 K, and expanded in the low-pressure turbine section to the condenser pressure. The water is a saturated liquid after passing through the water heater and is at the heater pressure. The flow rate of steam is 20 kg/s. Determine the power produced.

6.33. A steam power plant is using an actual reheat regenerative Rankine cycle. Steam enters the high-pressure turbine at 10800 kPa and 773.15 K, and the condenser operates at 15 kPa. The steam is extracted from the turbine at 2000 kPa to heat the water in an open heater. The steam is extracted at 475 kPa for process heat. The water is a saturated liquid after leaving the water heater. The steam flow rate is 30.8 kg/s. Determine the power produced.

6.34. A steam power plant is using a geothermal energy source. The geothermal source is available at 220°C and 2320 kPa with a flow rate of 180 kg/s. The hot water goes through a valve and a flash drum. Steam from the flash drum enters the turbine at 550 kPa and 428.62 K. The discharged steam from the turbine has a quality of $x_4 = 0.95$. The condenser operates at 40 kPa. The

water is a saturated liquid after passing through the condenser. Determine the net work output.

6.35. A steam power plant is using a geothermal energy source. The geothermal source is available at 220°C and 2320 kPa with a flow rate of 50 kg/s. The hot water goes through a valve and a flash drum. Steam from the flash drum enters the turbine at 550 kPa and 428.62 K. The discharged steam from the turbine has a quality of $x_4 = 0.90$. The condenser operates at 15 kPa. The water is a saturated liquid after passing through the condenser. Determine the net work output.

6.36. A cogeneration plant is using steam at 5500 kPa and 748.15 K to produce power and process heat. The amount of process heat required is 10000 kW. Twenty percent of the steam produced in the boiler is extracted at 475 kPa from the turbine for cogeneration. The extracted steam is condensed and mixed with the water output of the condenser. The remaining steam expands from 5500 kPa to the condenser conditions. The condenser operates at 10 kPa. Determine the network output.

6.37. A cogeneration plant is using steam at 8400 kPa and 773.15 K (see Fig. 6.14). One-fourth of the steam is extracted at 600 kPa from the turbine for cogeneration. After it is used for process heat, the extracted steam is condensed and mixed with the water output of the condenser. The rest of the steam expands from 600 kPa to the condenser pressure of 10 kPa. The steam flow rate produced in the boiler is 60 kg/s. Determine the work output.

6.38. A cogeneration plant uses steam at 900 psia and 1000°F to produce power and process heat. The steam flow rate from the boiler is 40 lb/s. The process requires steam at 70 psia at a rate of 5.5 lb/s supplied by the expanding steam in the turbine. The extracted steam is condensed and mixed with the water output of the condenser. The remaining steam expands from 70 psia to the condenser pressure of 3.2 psia. Determine the work output.

6.39. One kmole of air is initially at 1 atm, -13°C, performs a power cycle consisting of three internally reversible processes in series. Step 1-2: Adiabatic compression to 5 atm. Step 2-3: Isothermal expansion to 1 atm. Step 3-1: Constant-pressure compression. Determine the net work output.

6.40. A steam power plant output is 62 MW. It uses steam (stream 1) at 8200 kPa and 550°C. The discharged stream (stream 2) is saturated at 15 kPa. If the expansion in the turbine is adiabatic, and the surroundings are at 298.15 K, determine the steam flow rate.

6.41. A steam power plant output is 55 MW. It uses steam (stream 1) at 8400 kPa and 500°C. The discharged stream (stream 2) is saturated at 30 kPa. If the expansion in the turbine is adiabatic, and the surroundings are at 298.15 K, determine the steam flow rate.

6.42. In a hydropower plant, a hydroturbine operates with a head of 33 m of water. Inlet and outlet conduits are 1.70 m in diameter. If the outlet velocity of the water is 4.6 m/s estimate the power produced by the turbine.

6.43. In a hydropower plant, a hydroturbine operates with a head of 46 m of water. Inlet and outlet conduits are 1.80 m in diameter. If the outlet velocity of the water is 5.5 m/s estimate the power produced by the turbine.
6.44. Consider a hydropower plant reservoir with an energy storage capacity of 1.5 10^6 kWh. This energy is to be stored at an average elevation of 40 m relative to the ground level. Estimate the minimum amount of water to be pumped back to the reservoir.
6.45. Consider a hydropower plant reservoir with an energy storage capacity of 2.0 10^6 kWh. This energy is to be stored at an average elevation of 460 m relative to the ground level. Estimate the minimum amount of water to be pumped back to the reservoir.
6.46. A farm of windmills supplies a power output of 2 MW for a community. Each windmill has blades 10 m in diameter. At the location of the windmills, the average velocity of the wind is 11 m/s and the average temperature is 20°C. Estimate the minimum number of windmills to be installed.
6.47. A farm of windmills supplies a power output of 3 MW for a community. Each windmill has blades 11 m in diameter. At the location of the windmills, the average velocity of the wind is 14 m/s and the average temperature is 20°C. Estimate the minimum number of windmills to be installed.
6.48. A farm of windmills supplies a power output of 4.2 MW for a community. Each windmill has blades 10 m in diameter. At the location of the windmills, the average velocity of the wind is 15 m/s and the average temperature is 20°C. Estimate the minimum number of windmills to be installed.

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